MIGRATIONS OF JUVENILE SOUTHERN ELEPHANT SEALS FROM MACQUARIE ISLAND

by

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for the degree of

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DECLARATION

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in this thesis and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgment is made in the text of this thesis.

John van den Hoff

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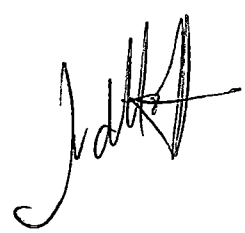

John van den Hoff

Frontispiece: Movement of a southern elephant seal pup at Macquarie Island
(Photograph by R. Waterhouse, 1972)

ABSTRACT

I analysed tag resight and at-sea location data collected for juvenile (>1 – 3 year-old) southern elephant seals (*Mirounga leonina*) from Macquarie Island to establish these particular objectives:

1. Identifying regions where the seals disperse to and/or migrate between.
2. Establishing a spatial scale for plotting and correlating geolocations with ocean features and zones.
3. Recording the important foraging areas essential to the survival of these seals.
4. Quantifying the degree to which the seals share their marine habitat with differing age groups and sexes of elephant seals, and with commercial fisheries.

Permanently marking seals provides information relating to haulout locality and timing, migration duration and age related dispersal. Southern elephant seals marked at Macquarie Island disperse to distant locations where they are sometimes seen during their moult and, for juveniles, a mid-year haulout period (July-August). Most (87%) of the seals resighted were within 1 000 km of Macquarie Island, and most commonly at Campbell Island (700 km to the north-east). The sex and age classes most likely to disperse there were males less than two years old. Male elephant seals of all ages were resighted significantly more often than females, the ratio being 2:1 ($P > 0.05$). Migration duration tended to increase with the seal's age but migration distance was underestimated from resight observations when compared with known telemetry records. Emigration from the Macquarie Island population appears limited. From the resight effort at Campbell Island during 1995 the maximum proportion of the juvenile population from Macquarie Island to haulout at Campbell Island was in the order of 0.0053.

I tested the location estimation performance of geolocation time-depth recorders (GLTDR) against a stationary site and free-ranging elephant seal locations established by satellite and global positioning system (GPS) telemetry. I found significant variation in latitude, but not longitude estimation, between individual GLTDRs within the same deployment period. This indicates a high level of confidence in longitude estimation if corrections for latitude are being made using remotely sensed data (e.g., sea-surface temperature) and/or seal behaviors such as dive depth and haulout. There was variability in location accuracy depending on

season and latitude as previous studies have found. At-sea GLTDR derived location estimates improved at higher latitudes where day length changes are greatest, seal travel rates decrease and locations are clumped in presumed foraging areas or haulout sites. Geolocation estimates improved as a consequence of deployment period, longer stationary periods produced better estimates with greater confidence. There was also considerable variation in daily location estimates of location during non-equinox periods at a stationary site. These were related to some measured weather conditions.

At-sea geolocations should be analysed using a scale of no less than ± 2.5° (5° grid square) at sub-Antarctic latitudes, and at least ± 2° (4° grid square) at higher latitudes during non-equinox periods if a high level of confidence (95%) in position estimation is required. For lesser degrees of confidence (68%), the scale can be decreased to ± 1.5° (3° grid square) at sub-Antarctic latitudes and probably at higher latitudes also, given that the accuracy of geolocation increases with increased latitude. I conclude that geolocation is a very useful method for tracking the pelagic movements of most land breeding marine birds, reptiles and mammals that make long (*ca.* 1 000 km) migrations to foraging grounds. The locations can be correlated to meso-scale ocean features and similarly scaled commercial fishing areas.

Twenty-two juvenile southern elephant seals aged 7 to 14 months were tracked as they departed Macquarie Island during 1993 and 1995. Migratory behavior and areas of concentrated activity, presumed to be pelagic foraging grounds, were established from location data gathered by attached geolocation time-depth recorders. The seals ranged widely from the island preferentially migrating to the south-east of Macquarie Island. Survivorship of seals that had been handled and fitted with GLTDRs was similar to free-ranging seals of the same age that had no instruments attached. Thus, the methodology used for this study appears to have no detrimental effect on survival and this gives confidence in the results of this study.

Although not statistically tested, the foraging activity of seals appeared to be associated with meso-scale oceanographic frontal systems and near bathymetric features, especially waters near the Antarctic Polar Front (APF), the Southern boundary of the Antarctic Circumpolar Current (SACC), the Marginal Ice-edge Zone (MIZ), and the Campbell Plateau. Seals commonly foraged in waters greater

than 3 000 m deep where the sea-surface temperatures were between 1.0 and 4.0° C unless they foraged over the Campbell Plateau where the sea-surface temperatures were about 8° C and the depth less than 2 000m.

The foraging areas for juvenile seals overlap those of adult female seals but the overlap is minimal in time and space because of the differing haulout behavior and diving ability of the age classes. Adult male seals forage too far to the south to overlap with juvenile seals of either sex but there appears to be an ontogeny of differential foraging migrations with male seals from Macquarie Island similar to that for northern elephant seals.

Southern elephant seals from Macquarie Island forage within managed fishery areas and in the high seas, an area of unregulated fishing. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) areas 58.4.1 and especially 88.1 were important foraging areas for juvenile elephant seals from Macquarie Island. Currently the overlap between fisheries and elephant seals from Macquarie Island appears minimal, but there is a lack of knowledge of the diet of southern elephant seals while at sea and in particular as they forage at the Antarctic continental margin.

ACKNOWLEDGEMENTS

I am grateful to the following people who made contributions to this thesis.

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Kai and Alia made no contribution to this thesis other than the fact that they were markedly absent, fed themselves at times and found time to play games when it counted. Special thanks to my father, Colin, who corrected my english, x'ed the tees and •'ed the eyes while I played golf.

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CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Southern elephant seals (*Mirounga leonina* L.) have a circumpolar distribution, breeding mainly on sandy beaches at sub-Antarctic islands lying close to the Antarctic Polar Front (Laws 1994). Four geographically and genetically distinct populations have been identified (Laws 1994, Slade 1997); the South Georgia stock, the Kerguelen stock, the Macquarie stock and the South American stock. Locations of the main breeding colonies are shown in Figure 1.1.

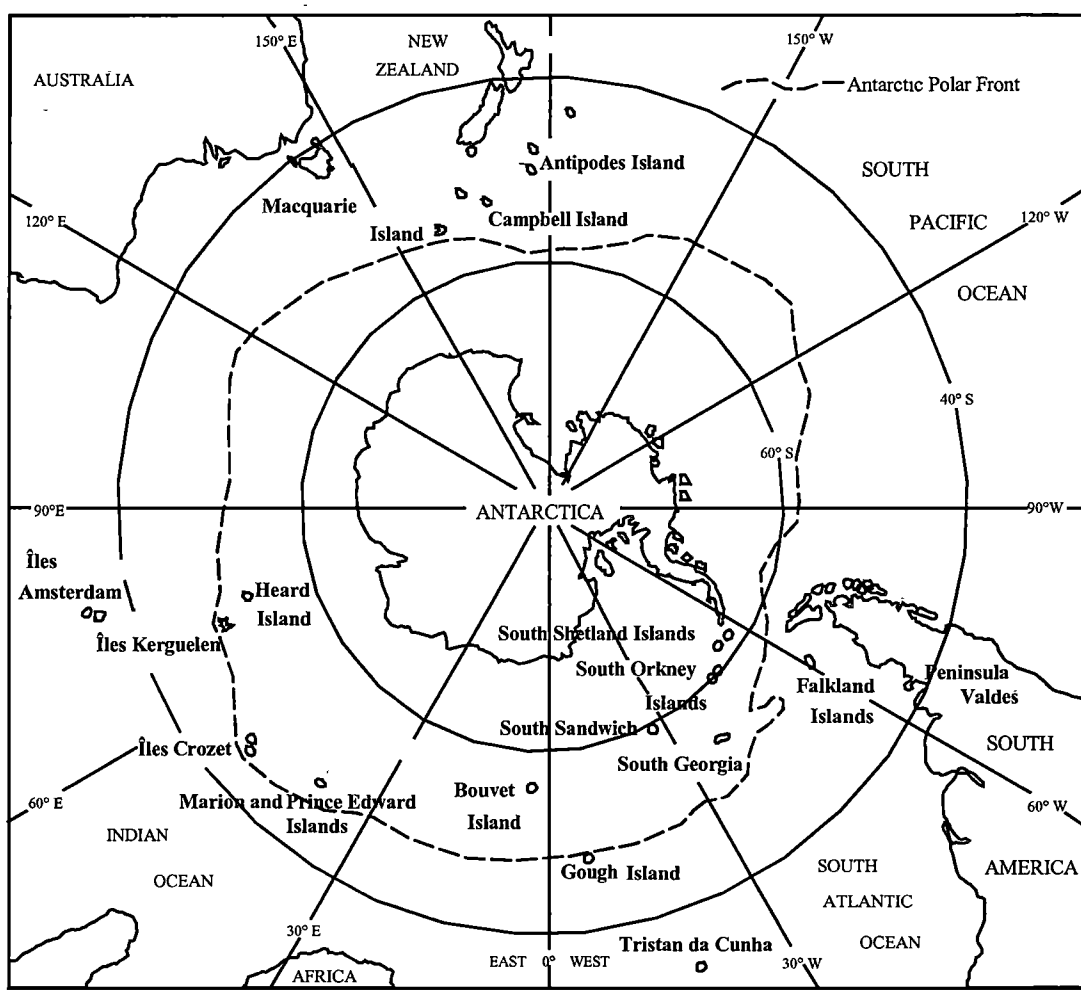

Figure 1.1: Map showing the main breeding sites (bold text) for the southern elephant seal (*Mirounga leonina* L.). and the average location of the Antarctic Polar Front.

Numerically, the southern elephant seal is one of the more abundant pinniped species in the world (Laws 1994). The male is the largest of any extant pinniped species, and reproductive males at Macquarie Island can be over five meters in length and reach a maximum weight of 3 700 kg (Ling and Bryden 1981), the average weight is between 1 500 and 3 000 kg. Reproductive females range in mass from 350 to 800 kg, average post-partum maternal mass at Macquarie Island being 500 ± 100 kg (Hindell and Slip 1997). Thus, breeding males may reach a mass of up to ten times that of breeding females.

While sexual dimorphism is distinct between adults, it is almost indistinguishable at birth and weaning. Males weigh 7-10% more at birth and only 4% more at weaning than females (McMahon *et al.* 1997). Mean birth weights range between 34 kg and 49 kg, and mean wean weights between 98 kg and 171 kg depending on sex and breeding location, the heaviest pups are produced at King George Island (Burton *et al.* 1997). Lactation (nursing) period also varies between breeding populations ranging from 21 to 24.5 days (McMahon *et al.* 1997). At Macquarie Island the pups are average in size. Females have a birth mass of 38 ± 5 kg and their wean mass is 116 ± 24 kg; male pups weigh 42 ± 6 kg at birth and 120 ± 27 at weaning. Nursing pups gain 3 $kg.day^{-1}$ for approximately 24.5 days (McMahon *et al.* 1997). The mass of pups at weaning is largely dependent on maternal pre-partum mass (Fedak *et al.* 1996).

Once weaned, the pups remain ashore and fast for a 3 - 9 week period during which they learn swimming and diving skills, sleep and decrease to 68 - 70% of their wean mass (Wilkinson and Bester 1990, Arnbom *et al.* 1993). Following the post-weaning fast, pups depart on the critical first foraging trip. Recent studies at Macquarie Island have shown that first year survivorship for a single cohort was in the order of 60% (McMahon *et al.* 1999) indicating this first foraging trip is difficult (Le Boeuf *et al.* 1994). The survivorship is similar to estimates from other populations (e.g., South Georgia and Marion Island) but is higher than previous estimates from Macquarie Island (Hindell 1991). The first foraging trip lasts for an average of 182 days and the pups gain 0.34 $kg.day^{-1}$ (Bell *et al.* 1997). Successful weaners increase their departure mass by an average 75% and those individuals that remain at sea for longer returned in better body condition (Bell *et al.* 1997). Early at-sea behavior of weaned pups is distinctly different to that of adults, the pups have

no diurnal pattern and make shallower, shorter dives (Hindell *et al.* 1999, Irvine *et al.* 2000). After 60 – 80 days the pups began to display behaviors more like that of the adults. Survivors of that first foraging trip return to their natal island and remain ashore for a mid-year haulout apparently resting. The seals then continue to cycle between foraging and haulout twice each year (Hindell and Burton 1988) progressively altering the timing of haulout to coincide with breeding.

Dramatic reductions in southern elephant seal numbers at key colonies occurred during the late 1800s and early 1900s as they were hunted for their oil. Since then the populations in the Îles Kerguelen and Macquarie Island stocks declined steadily over a period of forty years (Burton 1986, Hindell and Burton 1987, Guinet *et al.* 1992, Bester and Wilkinson 1994). More recently the populations at South Georgia, Sea Lion Island (Faulkland Islands), Marion Island, Îles Kerguelen and Heard Island appear to have stabilised or are little changed over the past decade or so (Laws 1994, Boyd, Walker and Poncet 1996, Galimberti and Boitani 1999, Guinet *et al.* 1999, Slip and Burton 1999, Pistorius and Bester 2002). At Macquarie Island the population decline continues (Australian Antarctic Division, unpublished data). A number of possible causes for the decline have been suggested by Hindell *et al.* (1994a). One hypothesis suggests increased pup mortality, perhaps owing to declines in prey availability, could be the ultimate cause for this long-term decline. Such an effect could present itself to either adult or juvenile seals while they forage. Thus, understanding the foraging ecology and at-sea distribution of southern elephant seals from stable and decreasing populations is important for establishing the factors that may influence their survival.

1.2 At-Sea Distribution

Study of the marine distribution and ecology of free-ranging southern elephant seals has concentrated upon the adult age classes. Telemetry studies have been used to track breeding male and female seals from most breeding sites to distant foraging grounds (e.g., Bester and Pansegrouw 1992, Bornemann *et al.* 2000, Campagna *et al.* 1999, Hindell *et al.* 1991a, Jonker and Bester 1998, McConnell *et al.* 1992a, McConnell and Fedak 1996, Slip 1997a). From these studies the marine distribution of adult seals is dependent on season and sex. Although never tested statistically, it has been shown that the foraging areas are predominantly open ocean frontal zones,

within the pack-ice outer edge or over shallow (<500 m) continental slopes where primary productivity is elevated.

There are few studies of juvenile elephant seals and those that have taken place found weaned pups, making their first pelagic migration from King George Island, utilised different areas for foraging than adult females (Bornemann *et al.* 2000). At Heard Island juvenile seals making their second trip to sea, foraged in areas similar to those used by adult females (Slip 1997a, b) but the sample size was small (n = 2). The marine distribution of elephant seals appears to differ between sexes, season and age classes if comparing adult females and weaners from King George Island is an indication, but not from Heard Island.

1.3 Tracking Marine Mammals for Research

Gaining an insight as to where, when and why marine mammals migrate requires a system for tracking their movements. Early, and recent studies, used individual marking techniques such as tags and brands to determine origin, dispersal, dispersion, haulout behavior, immigration and emigration of large numbers by resighting them at different locations and times of the year (references in van den Hoff 2000a, Chapter 2 this volume). The value of studies such as this is that very large numbers of individuals can be observed for very long periods, up to 23 years (Hindell and Little 1988). The main draw back is that no at-sea information such as foraging area, diving behavior and position are obtainable from marked only seals.

The tracking of individual seals is generally associated with the use of a telemetric method of some type. The individual is fitted with an active transponder that transmits a signal to a receiver. Ultra-high-frequency (UHF) and very-high-frequency (VHF) tags are commonly used, UHF tags with satellite based systems, VHF tags are the "classical" radio transmitter (Priede 1992). For pinnipeds, both frequencies have their uses, UHF can be used to track seals for long at-sea migrations while VHF tags are useful for relocating instrumented individuals and tracking local on shore movements during moult and haulout. The cost of UHF tracking is high, both in purchasing costs for instruments and for satellite usage. The real value in UHF technology is in the gathering of accurate, real time location

and behavior data for individuals who are successful and for those who perish while at-sea.

Given the high cost of the above telemetry methods, a cheaper archival instrument was developed (DeLong *et al.* 1992). Geolocation, as the method became known, used differences in day-length around the globe to determine the movements of northern elephant seals, and is now used to track other far ranging species (Wilson in press). The spatial scale is suitable for species that forage over large-scale ocean features (DeLong *et al.* 1992). However, only two locations per 24-hour period are possible at best, and only records from successful individuals are obtained, ie. seals that return and are recaptured. Also an animals latitude cannot be located with any confidence during equinox periods when day-length is similar around the globe.

1.4: Commercial Fisheries and Management Issues in the Antarctic and sub-Antarctic

Krill (*Euphausia superba*) catch dominates the commercially fished species in the Southern Ocean that overlap the diet of southern elephant seals, and two fish species, Patagonian toothfish (*Dissostichus eleginoides*) and ice-fish (*Champsocephalus gunnari*), currently contribute much of the remainder to the commercial catch overlap (Figure 1.2). Krill have been targeted since the 1960s with varying degrees of intensity, and recently the fishery has collapsed because of economic factors and market demand. In contrast, toothfish and ice-fish have shown a markedly different recent trend. Ice-fish has had a boom catch of 235 296 tonnes (t) in 1978 and a bust in 1992 of 66 t (FAO 1997), presumably due to reduced demand. Toothfish is the important fishery in the Southern Ocean at the present time. Catches increased to 14 000 t in 1992 and have remained over 5 000 t since then (FAO 1997). Illegal, unreported and unregulated fishing for toothfish is a major problem, and thus the reported catch tonnage for this species is probably under represented.

More important, by mass, to elephant seal diet than krill, ice-fish or toothfish is the squid *Martialia hyadesi* (Slip 1995, Burton and van den Hoff in press). The squid has been recognised as having commercial potential, has been fished commercially (Figure 1.2), and is the subject of exploratory fishery in 2000/01

(Commission for the Conservation of Antarctic Marine Living Resources; CCAMLR Conservation measure 213.XIX).

Management of species that overlap the commercial fishery and southern elephant seal diet is the mandate of CCAMLR (krill, toothfish, ice-fish and *Martialia*), Australia (toothfish and *Martialia*) and New Zealand (toothfish) fisheries authorities. They are, in-part, managed by the implementation of a total allowable catch limit (TAC) which is, largely, ignored in the case of toothfish, and much under-utilised for krill. The TAC in the jig fishery for *Martialia* has been set at 2 500 tonnes in area 48.3 for the year. Expansion of this fishery requires strong management because *Martialia hyadesi* is an important prey species for many Southern Ocean predators (Rodhouse 1990).

Commercial fisheries in the Antarctic are managed through the implementation of ecosystem and precautionary based approaches that: 1). seek to maintain the ecological relationships between harvested, dependent and related species, and 2). prevent or minimise any changes that are not reversible within 20-30 years. These are complex tasks, as they not only require monitoring of the fishery but also the ecosystem components (e.g., krill, species eaten by krill, species that eat krill and those species that eat krill predators).

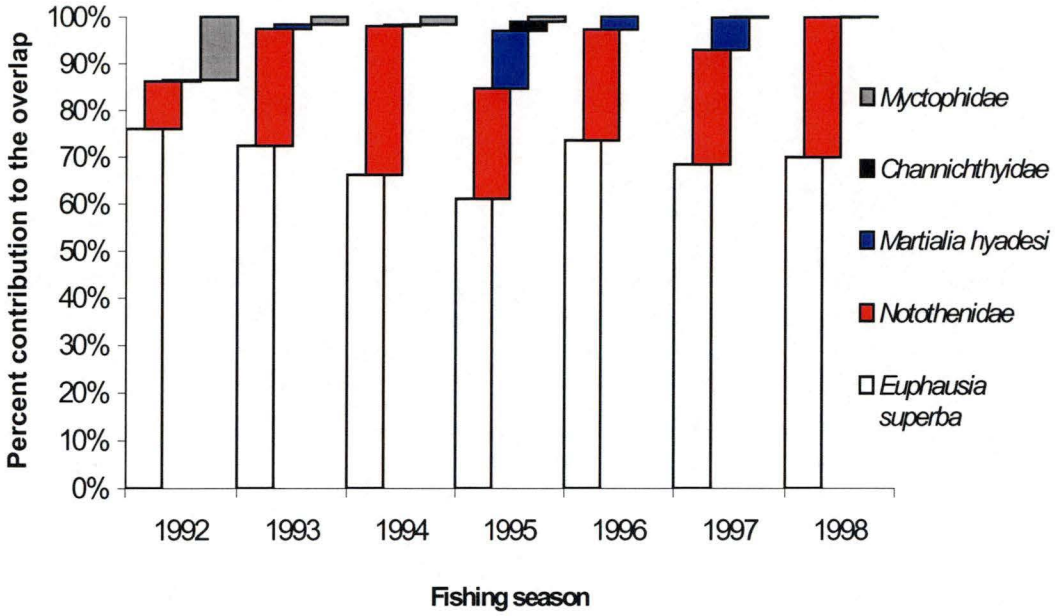

Figure: 1.2. Percent contribution of fish, squid and crustacean taxa, that overlap both the diet of elephant seals and commercial fishing, to commercial fisheries in the southern hemisphere between 1992 and 1998. (Source: FAO Vol 86/1 1998, re-drawn from Burton and van den Hoff, in press).

1.5 Thesis Objectives, Structure and Definitions

This study investigates the dispersion and foraging regions of juvenile southern elephant seals from Macquarie Island. The aims are to further an understanding of which geographic regions within the Southern Ocean are important to the survival of juvenile southern elephant seals and whether the feeding grounds of this major Antarctic predator, of which the population is decreasing, overlaps with commercial and exploratory fishing activities. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is obliged to ensure that fisheries practices maintain ecological relationships and to provide for the recovery of depleted species. This study will contribute to Antarctic ecosystem modelling and the conservation of the southern elephant seal.

Following a brief introduction to the species, Chapter 2 documents sightings of marked elephant seals at locations distant from Macquarie Island to establish age-related dispersal and migratory patterns of elephant seals born on the island. The sightings allow some estimation of migration duration, sexual preference for haulout

sites, foraging range and travel rates. Chapter 3 investigates the error associated with, and confidence limits around, estimates of seal location made by geolocation. The errors and confidence limits are used to provide a spatial scale for plotting the movements and marine area usage for far ranging pinniped species. Chapter 4 employs the results from chapter 3 for plotting the at-sea locations of juvenile elephant seals from Macquarie Island. The chapter identifies the seals' main foraging areas and relates their usage to ocean environments, adult seal distribution and commercial fisheries that are increasing in intensity throughout the Southern Ocean.

Odum (1959) defines population dispersal is the movement of individuals or their disseminules into or out of a population or population area by emigration (a one-way outward process), immigration (one-way inward) or migration (periodic departure and return). I use the terms dispersal, dispersion and migration in this thesis to mean the following: dispersal is the change in an individuals' distribution from birthsite to breeding site (Nichols 1970) and is best described as emigration; dispersion is the changing distribution of an animal during its life that includes migration which is an extreme form of dispersion involving regular two-way movement over large distances (Lack 1954 in Nichols 1970). For a migration to be completed there is no requirement for the individual to return there to breed as Caughley (1977) requires, indeed the juvenile seals used in this study are below breeding age but do perform regular two-way movements over large distances.

The chapters in the thesis are prepared as separate papers and thus some repetition of methodology and results is unavoidable. I am the senior author on each paper and I have taken responsibility for the research and presentation of the data published herein unless otherwise acknowledged.

CHAPTER 2[1]

RECENT RESIGHT RECORDS OF SOUTHERN ELEPHANT SEALS (*Mirounga leonina* L.) MARKED AT MACQUARIE ISLAND

2.1 INTRODUCTION

Prior to advances in satellite and microelectronic technology early studies of elephant seal migration patterns relied on marked animals to determine dispersion and migration (Ingham 1960, Nicholls 1970, Burton 1985). Juvenile and adult males branded on Macquarie Island dispersed to Campbell Island and males branded on Campbell Island dispersed to Macquarie Island (Nicholls 1970). Burton (1985) reported that immature male seals migrated from the Vestfold Hills to Heard Island, concluding that the seals originated from Heard Island. Mark-recapture studies can still provide valuable data on animals from all age and sex classes that can be difficult to obtain with more individual based studies such as satellite telemetry. For example the longest seal migration (10 000 km) comes not from telemetry, but from the sighting of a branded seal from Macquarie Island (54°37'S, 158°52'E) at Peter 1 Øy (68°51'S, 90°35'W, Hindell and McMahon 2000).

Macquarie Island is the major breeding site for southern elephant seals in the south Pacific Ocean, with small rookeries also found at Campbell and Antipodes Islands (Laws 1994). The population of elephant seals at Macquarie Island was about 86 500 in 1985 (Hindell and Burton 1987) and is presently decreasing at 1.2% per annum (Australian Antarctic Division unpublished data). Documenting and understanding dispersal is important for population studies where estimates of survivorship, immigration and emigration are required. Management objectives also take account of migratory characteristics such as feeding range, diet, genetic exchange and possible pathological interactions, all of which can be better understood from marked individuals with known histories.

Within the southern Indian and Pacific Oceans, unmarked elephant seals have been sighted on the West Australian coast (Mawson and Coughran 1999),

[1] Published as van den Hoff, J. 2001. Dispersal of southern elephant seals (*Mirounga leonina* L.) marked at Macquarie Island. Wildlife Research, 28:1-6.

Tasmanian coast and islands (Pemberton and Skira 1989) and New Zealand (Mills *et al.* 1977). Since 1951, weaned and older southern elephant seals have been tagged and/or branded at Macquarie Island, on an intermittent basis, for demographic studies. Two major efforts to hot-iron brand, and therefore permanently mark weaned elephant seals took place, one between 1951 and 1965 and the other between 1993 and 1999. These markings allow, amongst other things, observations on dispersal (Nicholls 1970) and those factors outlined above.

The aim of this study was to use sightings of marked elephant seals to establish basic, age-related, dispersal patterns and behavior for southern elephant seals from Macquarie Island. The sightings also allow some estimation of elephant seal migration duration, emigration and foraging location.

2.2 METHODS

Records of marked elephant seals that were resighted away from their natal island, Macquarie Island, are kept as part of a long-term demographic study. Currently, 27 663 southern elephant seals have been marked on Macquarie Island by permanent hot-iron branding on each of the rear flanks (Ingham 1967, McMahon *et al.* 1999) and/or by placing a coloured, serially numbered plastic tag (Dalton Supplies, Australia) in the inter-digital webbing of one or both hind flippers. Thus some seals had brands and flipper tags. At Macquarie Island some 2 000 weaned pups were branded during November each year between 1993 to 1999, giving a total of 14 000 recently marked individuals.

Resights of marked seals have come from a variety of sources, most prevalent being the Department of Conservation (DOC), New Zealand for Campbell Island. Between 1994-1996 resighting of elephant seals at Campbell Island was routine and cooperative between there and Macquarie Island (Clive McMahon personal communication). Since DOC staffing levels at Campbell Island were reduced in late 1995, tourist ship visits to New Zealand's offshore islands have become another source for resights of elephant seals from Macquarie Island. The resight effort at Macquarie Island was on a daily basis for the isthmus area, every 10 days for the northern third of the island and every month for the remainder of the island (McMahon *et al.* 1999).

Details relating to each resight were: identification number, date, sighting location, sex, age and where possible, moult status (not moulting/moulting). Each record was stored in a database maintained at the Australian Antarctic Division (AAD). The proportion of the total number of seals branded at Macquarie Island since 1993 and resighted at Campbell Island was calculated from the accumulating number of branded seals (2 000/year between 1993 and 1999) after survivorship was accounted for in each age cohort (AAD unpublished data).

Odum (1959) defines population dispersal is the movement of individuals or their disseminules into or out of the population or population area by emigration (a one-way outward process), immigration (one-way inward) or migration (periodic departure and return). Some seals have not been seen to return to Macquarie Island since the last resight at the distant haulout site. Due to the high degree of site fidelity in this species (Nicholls 1970, Hindell and Little 1988) and the consistent searching for marked seals (McMahon *et al.* 1999) those seals would likely have been resighted if they were still alive and had returned to Macquarie Island. Tagged seals cannot be assumed dead or to have emigrated because they may have lost their tags and for this reason I report migration characteristics for tagged seals only if they were resighted again in the future.

I used tagged and branded seals resighted between the moult/mid-year haulout/moult periods within a year (n = 28) to calculate time lapsed between resights which gave an estimate of the maximum duration for the seals migration. I used a *t*-Test to test statistically for differences between means and chi-squared (χ^2) tests of independence to test the proportion of the sexes sighted.

2.3 RESULTS

Since November 1978, 97 resights from 58 individual southern elephant seals of both sexes and differing age classes were made at 11 localities other than Macquarie Island (Figure 2.1). Seals were sighted in all months with a peak occurring between November and January (juvenile moult) while a smaller peak occurred between July and August (mid-year haulout, Figure 2.2). Males significantly out-numbered females 39 to 19 (ratio 2.05:1, $\chi^2 = 6.88$, $df = 1$, $P < 0.01$).

Seventy-seven (77) percent of all known-age seals were < 2 years old (range 6-192 months; Figure 2.3). Male seals, aged 24 months or less accounted for 54% of all the seals resighted. The oldest known-age (192 months) seal resighted in this study was female, she was hot-iron branded in November 1962, pupped at Macquarie Island in October 1978, moulted at Campbell Island in November of that year, pupped again at Macquarie in October 1980 and was last resighted at Macquarie Island in October 1985 at age 23 with a pup (Hindell and Little 1988). The youngest seal (6 months) was male, he was branded in October 1994, resighted while hauled-out at Campbell Island in March 1995, and he had returned to haulout again at Macquarie Island in May 1995.

Seventy-nine (79) percent of the resighted seals were at Campbell Island (Figures 2.1 and 2.4). The next most important location was the Auckland Islands (Enderby and Dundas Islands) with 10% of all seals resighted there. Both the Campbell and Auckland Islands are approximately 700km from Macquarie Island. One male seal travelled to Trefoil Island, NW Tasmania (40°38'S, 144°41'E) and this is the most distant locality (1 875 km) reported in this study, he was resighted back at Macquarie Island on 20/April/2000. Only 9 of 58 (15%) seals were resighted further than 1 000 km from Macquarie Island. Thirty-eight seals made 42 migrations (ie. M.I. → elsewhere → M.I.), three seals died at the distant location and 17 seals have yet to be resighted (Table 2.1).

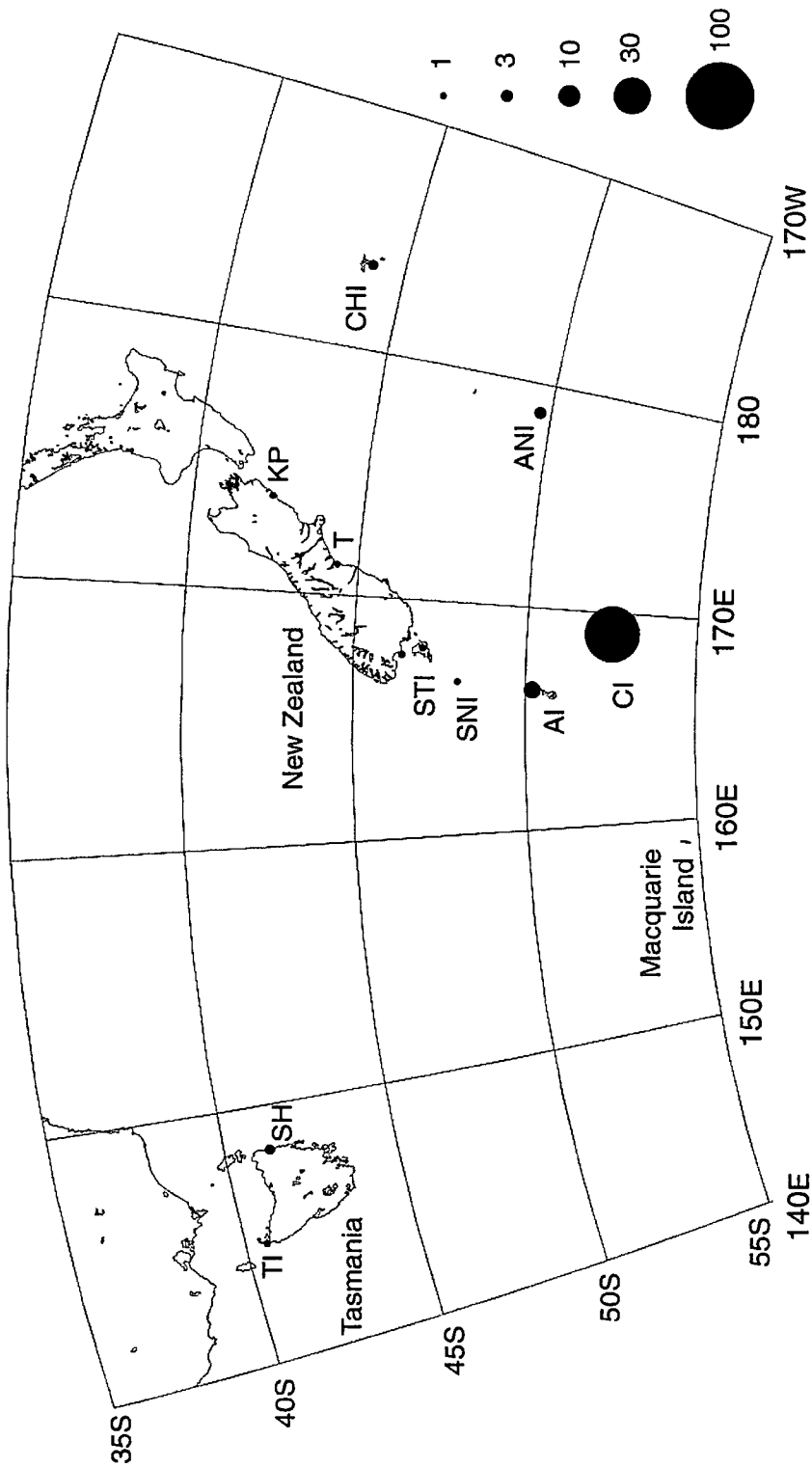

Figure 2.1: Map of the study region with locations where marked seals have been resighted. (The size of the black dot relates to the number of resights.) TI = Trefoil Island, SH = St. Helens, CI = Campbell Islands, AI = Auckland Islands, SNI = Snares Islands, STI = Stewart Island, ANI = Antipodes Islands, CHI = Chatham Islands, KP = Kaikoura Peninsula, T = Timaru.

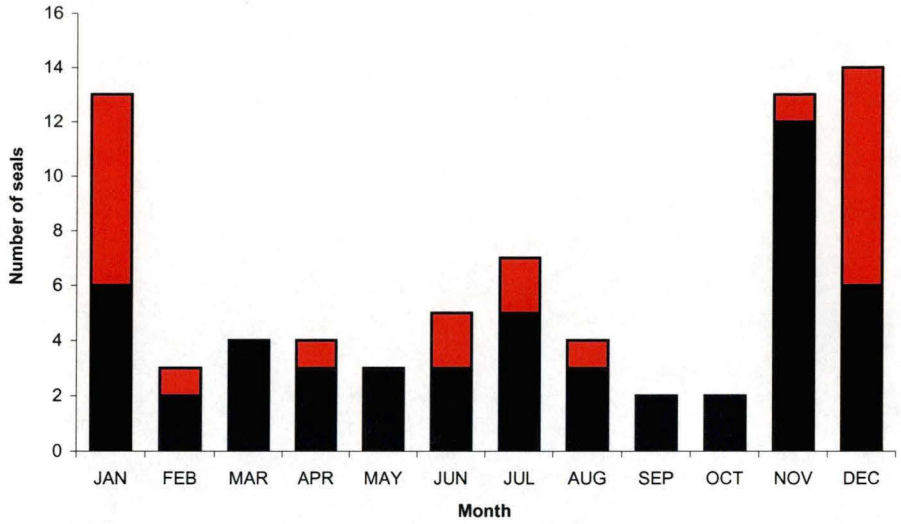

Figure 2.2: Numbers of marked southern elephant seals observed per month at all localities distant from Macquarie Island. Black bar = male

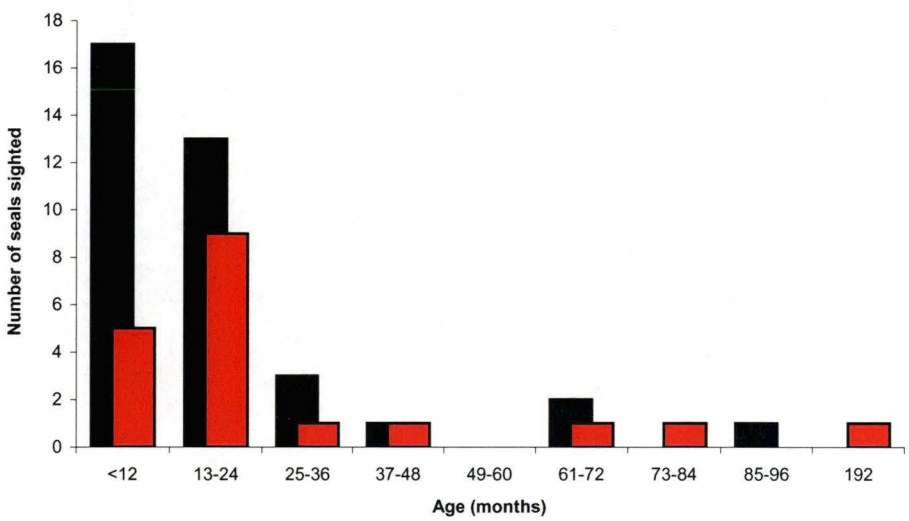

Figure 2.3: Age-frequency distribution of known age male and female southern elephant seals resighted at locations away from Macquarie Island. Black bar = male

Three sub-adult to adult age (>36 months) male seals made repeated, and sometimes consecutive, migrations to Campbell Island (Table 2.2). One sub-adult male (B2797) successfully migrated three times between Macquarie and Campbell Island, the last sighting of the animal was at Campbell Island. He gradually timed his arrival at Campbell Island to coincide with the breeding season, arriving earlier each year until he hauled out at Campbell Island in October. Seal B2797 has not been resighted at Macquarie Island in over 3 years and has either lost his tag, died or may have emigrated and joined the breeding males at Campbell Island. In contrast, male seal B1254 was seen in the breeding season at Macquarie Island and only during the moult at Campbell Island. Only one juvenile female seal has been seen at Campbell Island on more than one occasion during the juvenile moult period (Table 2.2).

Table 2.1: Numbers of complete and incomplete migrations from Macquarie Island (number of seals in parentheses). The incomplete migration category relates to seals not yet resighted after having been seen at a dispersal site. Dead seals were found dead at the distant site.

Sex	Complete migrations	Incomplete migrations	Dead
Male	27 (24)	12	3
Female	15 (14)	5	0
Total	42 (38)	17	3

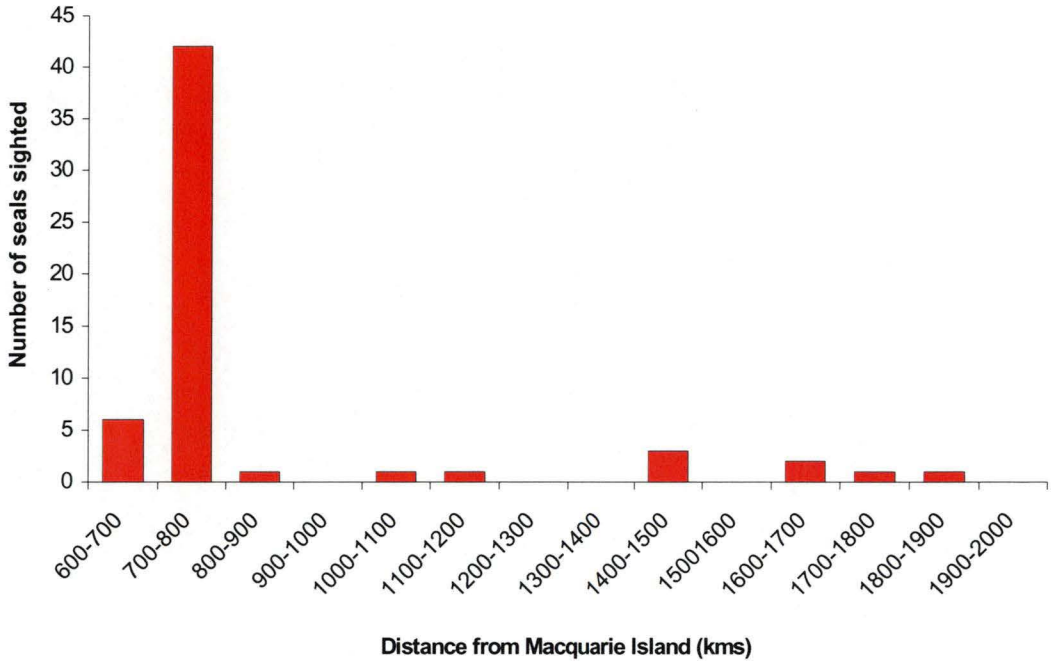

Figure 2.4: Frequencies of southern elephant seals travelling to locations distant from Macquarie Island. The dispersal distance is shown. Doubling the distance will give a minimum migration distance.

Table 2.2: Seal number, sex, age, and resight time for seals making multiple migrations from Macquarie Island to Campbell Island. (M = male, F = female, A = adult, SA = sub-adult)

	Sighting location, month and year (19xx).		
Seal number/Sex/Age	M.I.	C.I.	M.I.
B1254/M/A	Oct. 88	Jan. 89	Aug. 89
	Oct. 89	Mar. 90	Sept. 90
	Sept. 90	Mar. 91	
		Feb. 92	Aug. 92
B2797/M/SA	Nov. 88	Nov. 91/Apr. 92	Aug. 94
	Sept. 94	Dec. 94	Sept. 95
	Oct. 95	Oct. 96	
B2890/M/A	Dec. 89	Apr. 91	Oct. 91
	Nov. 91	Feb. 92	Oct. 93
K887/F/17 – 39 months	Dec. 96	Feb. 98	Apr. 99
	Jun. 99	Dec. 99	

Male seal migration duration increased with age (Table 2.3). Females tended toward this pattern, however sample sizes in age classes < 12 and 24+ months were low. Migration duration for yearling (12 - 24 month old) seals were not significantly different between the sexes (t statistic = 0.1 and 0.68 respectively, df = 13, $P >> 0.6$). Other age classes lacked a sufficient sample size for any comparisons to be made.

There is a very large pool of marked elephant seals from Macquarie Island and all of these seals must leave the island to forage during a pelagic migration phase. The number of resights of branded only seals at Campbell Island expressed as a proportion of branded seals, aged 1 to 6 years, in the Macquarie Island population is shown in figure 2.5. The coordinated resighting effort at Campbell Island in 1995 produced the most resights in that year verses any other, but only a small proportion (0.005) of all the branded seals available were seen there, indicating the vast majority of the seals were elsewhere.

Table 2.3: Estimates of migration duration (days between resights) for male and female elephant seals of various age classes from Macquarie Island. (mean ± SE, *n* = number of migrations recorded).

Sex	Age (months)	Days between sightings for migrating seals	*n*
M	<12	110 ± 28	4
M	12+	138 ± 9.5	8
M	24+	200 ± 15.5	2
M	>36	93 ± 31.4	5
F	<12	229	1
F	12+	157 ± 21.5	7
F	24+	182 ± 42.1	2

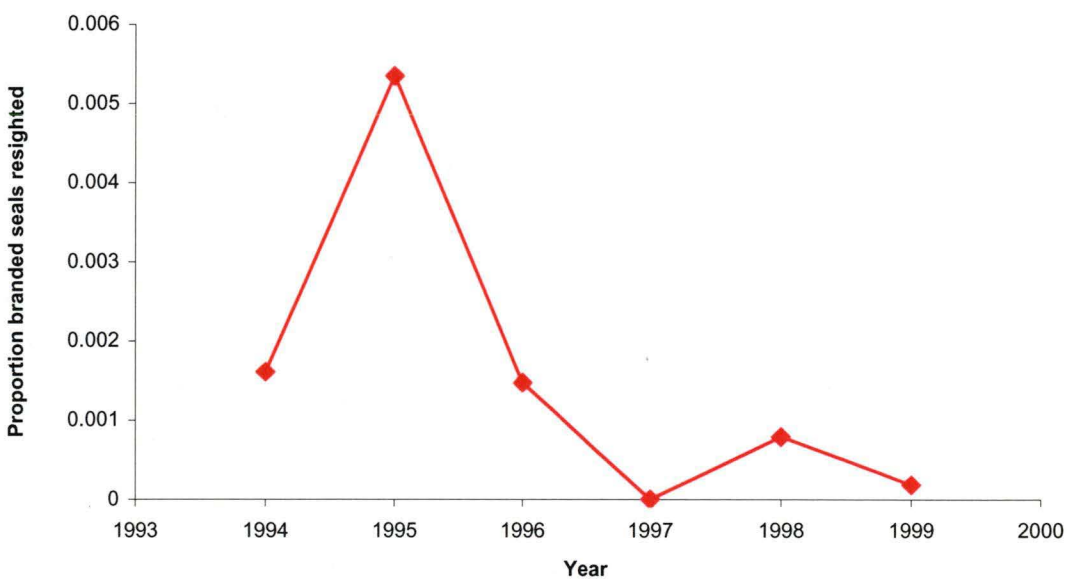

Figure 2.5: Proportion of the total number of southern elephant seals branded at Macquarie Island and resighted at Campbell Island over time.

2.4 DISCUSSION

Dispersion of marked juvenile and sub-adult male and female southern elephant seals from Macquarie Island to Campbell and Chatham Islands has been previously recorded (Carrick *et al.* 1962). Dispersion also occurred in reverse, one sub-adult male seal branded at Campbell Island was resighted at Macquarie Island (Nicholls 1970). However, these studies did not show evidence or reported instances of these seals ever completing their migration by returning to Macquarie Island. This study showed that elephant seals from Macquarie Island not only dispersed to haulout at 11 sites distant from their natal island but also return to Macquarie Island to complete a migration (as defined by Odum 1959).

Some marked seals from Macquarie Island were resighted at locations on the Tasmanian mainland and at an offshore island close to Bass Strait. Breeding colonies of southern elephant seals were once located on some of the Bass Strait Islands and there is fossil evidence of elephant seals on Tasmania's west coast (Bryden *et al.* 1999, references in Pemberton and Skira 1989). Sightings of elephant seals in Tasmania are rare and were previously of unmarked individuals of uncertain origin. The resights described here strongly suggest that unmarked elephant seals seen on the Tasmanian mainland and offshore islands (Pemberton and Skira 1989) originate from Macquarie Island because the Tasmanian coast is within their dispersal range. The populations may have had genetic and pathological exchanges in historical times.

Other than proximity, there may be some link between Macquarie Island and New Zealand's sub-Antarctic islands, in particular Campbell Island. Juvenile seals hauled-out at those islands may have recently foraged over the Campbell Plateau and have not travelled back to Macquarie Island in order to remain near the feeding grounds. Many and multiple sightings of marked seals at Campbell Island combined with geolocation tracking of juvenile seals from Macquarie Island, which placed their locations close to Campbell Island, the Antipodes and Auckland Islands (van den Hoff unpublished data), support this notion, particularly for young seals.

Male elephant seals were the most sighted sex (2:1, $P > 0.05$), particularly at age two-years or less, but the sex ratio at birth is equal (McMahon *et al.* 1997). Adult female elephant seals from Macquarie Island are highly philopatric (Hindell

and Little 1988) and become reproductively active earlier than males (Laws 1994, McMahon *et al.* 1997) and this may account for the lesser number of juvenile females resighted at distant locations. However, figure 2.3 suggests philopatry strengthened for both sexes after they reach 3 years of age, not just females. The disparity in the sex ratio is likely to be related to foraging area preference. Three times more underyearling male than female seals from Macquarie Island were hauled out at island sites on the Campbell Plateau. Underyearling male seals were also tracked to the Campbell Plateau in the ratio 3 males to 1 female (Chapter 4). Young males appear to favour foraging and haulout sites on the Campbell Plateau early in their life while females do not. Tierney (1977) found that elephant seals moulting at the Vestfold Hills on the Antarctic continent had a sex ratio of 133 males to 1 female. This ratio may be compounded by the presence of a seasonal sea ice belt that may exclude adult females from this site during their moult period (Bester 1988). There are no complications with sea-ice at the sites reported herein and the lack of sea-ice may have contributed to the greater parity between the sexes in this study. Wilkinson and Bester (1990) reported that the tendency for seals to relocate on Marion Island was also in favour of dispersing underyearling males.

Male seals dispersing from Macquarie Island may breed at distant Campbell and Antipodes Islands (Laws 1994). The observation that sub-adult male B2797 synchronised his haulout behavior at Campbell Island with the breeding season and the fact that he has not been seen in over three years at Macquarie Island indicates breeding dispersal (emigration) is possible. Death or tag loss could be the alternative fates of this particular seal. Survivorship for seals ages 6 years or greater is in the order of 82% (AAD unpublished data) and single tag loss is in the order of 17% (Clive McMahon personal communication), suggesting the seal may be alive with his tag intact. Sub-adult males not seen to return to Macquarie Island may emigrate but only at a very low rate.

During 1995, the resighting effort at Campbell Island was coordinated with Macquarie Island and this may in part explain the greater numbers of seals resighted at Campbell Island than elsewhere. However, elephant seals are conspicuous and prefer to haulout on sandy beaches rather than rocky substrate (Le Boeuf and Laws 1994). Thus, if the seals haulout at inhabited sites on New Zealand and Tasmanian coasts there is a good chance that they will be seen, particularly during the summer

months when moulting. When all the resight records are combined, more seals were seen during the annual moult than the mid year haulout as was the case at Macquarie Island (McMahon *et al.* 1999). This finding could be linked to the longer periods seals spend ashore during the annual moult in summer (22 days) compared to 11 days during the winter mid year haulout (McMahon *et al.* 1999) thus giving the seals a greater probability of being seen.

Male and female elephant seals aged three years or less appear to have a synchronised haulout behavior in the mid-year and the annual moult (Hindell and Burton 1988, Slip and Burton 1999). All seals continue to have two haulout periods but the timing changes for females after age three as their behavior abruptly changes: the mid-year haulout lapses to the breeding haulout in October and the moult period is confined to January (Hindell and Burton 1988). The females branded at Macquarie Island are just now reaching breeding age and are being resighted with pups in the breeding season at their natal island but the resight effort at Campbell Island has fallen away in recent years. The degree of emigration for female elephant seals from Macquarie Island could be more accurately calculated if there was a concerted resight effort at Campbell Island during the breeding season in October. Male seals reach sexual maturity later than females (Laws 1994) and thus retain the biannual haulout behavior characteristic of elephant seals aged three years or less. The haulout behavior appears to change at a different rate than that of females, males slowly coinciding their haulout with the breeding period (Carrick *et al.* 1962) and this may explain why more males than females were seen in the mid-year (Figure 2) at locations described herein. Winter haulout by southern elephant seals at Marion Island was favored by males aged >1 year, but the sex ratio was equal in the first year of life (Kirkman *et al.* 2001).

The resight data show that very few juvenile seals haulout further than 800 km from Macquarie Island but haulout site does not necessarily reflect distribution at sea (Burton 1985, Bester 1988), rather it reflects the distribution of haulout sites. The average foraging migration range (the straight line distance between Macquarie Island and the furthest located position from at-sea geolocation data) is indeed much larger than this; approximately 1 700 km (Chapter 4). Few (4) seals foraged north-east of Macquarie Island, the seals preferring forage areas to the south-east and south-west in ocean frontal zones. Recently, eight unmarked juvenile elephant seals

(perhaps from Macquarie Island) were seen during the moult period at Maatsuyker Island (43°39'S, 146°17'E, M. Jenkins and Fiona Hume personal communication). The island is some 1 500 km distant from Macquarie Island, and well outside the 800 km radius the resight data suggests most seals stay within. Thus, the seals' migration distance, as calculated by resight data, underestimate true migration distance, but the resights do indicate foraging may occur in the oceans adjacent to the haulout sites. If foraging grounds were assessed from tracking only then the importance of some areas may be under-represented from the smaller sample sizes.

Migration duration (taken here as the time lapsed between resights at haulouts) tended to increase with age (Table 3). There was no statistical difference between sex within the yearling age class. Other age classes in this study lacked the sample size for meaningful statistical comparisons. From telemetry studies, level of performance (travel speed and days at sea) increased, but was not statistically different, for northern elephant seals as they grew older from 9 to 27 months (Le Boeuf *et al.* 1996). Tracking of marked seals from Macquarie Island has shown that underyearling seals were at sea for an average of 121 and 117 days for female and males, respectively (Chapter 4). The values for tracked male underyearlings are similar to the values found from resight records in this study.

The pelagic migration of any southern elephant seal is primarily to hunt for prey in order to fatten, grow and then return to land with sufficient reserves of stored blubber for the moult, breeding season and, for some age classes, probably to rest (see Kirkman *et al.* 2001). Permanently marking large numbers of seals and resighting those individuals of known age and life-history contributes much to our understanding of seal behavior, population movements and interactions. For example, rates of genetic and pathological exchange between populations; dispersal destinations and survivorship of individuals while at sea foraging, a critical period in any seals life, can be established with precision and detail.

This study showed predominantly male elephant seals aged 24 months or less migrate to 11 sites located on the Campbell Plateau and around Tasmania. The seals haulout there to moult and rest but some 29% did not return to Macquarie Island and 3% died at the distant haulout site. Food availability near their haulout sites, predation, disease and disorientation while migrating are possible factors

contributing to elephant seal mortality while at sea. Loss of the flipper tags, on tagged only seals, could account for their apparent loss from the population.

CHAPTER 3[2]

ESTABLISHING THE APPROPRIATE SPATIAL SCALE FOR DISPLAYING GEOLOCATION ESTIMATES FOR THE AT-SEA POSITION OF FAR-RANGING MARINE VERTEBRATES

3.1 INTRODUCTION

Marine birds (e.g., wandering albatross, Weimerskirch *et al.* 1992), reptiles (e.g., sea turtles, Papi *et al.* 1997) and mammals (e.g., elephant seals, Slip *et al.* 1994) often migrate long distances between their breeding locations and foraging grounds. The conflicting requirements of a suitable breeding environment and productive waters for foraging necessitate these long migrations. Southern elephant seals breeding in the Indian Ocean sector of the Southern Ocean illustrate this very well. The southern elephant seal preferentially breeds on gently sloping sandy beaches or spits on sub-Antarctic islands (Le Boeuf and Laws 1994), but they will pup on shingle, cobble and boulder beaches, and vegetated areas (Marthan Bester, University of Pretoria personal communication). Both sexes fast during the breeding season and thus their blubber reserves must be capable of sustaining their activities while ashore for extended periods. Breeding males are ashore for 4 months or more, and their mass loss can be in the order of 33% (1 000+ kg) during the breeding season (Deutsch *et al.* 1994). Successful breeding is likely to be linked to successful foraging and given that elephant seals are large mammals that accumulate large blubber stores during foraging periods their prey must be high in number and/or energetic value. Prey suitable for adult and juvenile seals appear to be located at foraging grounds distant from the breeding islands. Their foraging migrations are to the Antarctic coast and oceanic locations (Hindell *et al.* 1991a, Bester and Pansegrouw 1992, McConnell *et al.* 1992a, McConnell and Fedak 1996, Slip *et al.* 1994, Slip 1997a, Jonker and Bester 1998, Bornemann *et al.* 2000) where their principal food is squid, fish and euphausids (Clarke and McLeod 1982, Daneri *et al.* 2000, Slip 1995, Chapter 4). Their migrations can be in the order of 4 000 km for adult seals (calculated from Slip *et al.* 1994) and as far as 10 000 km for juveniles (Hindell and McMahon 2000), though this migration appears to be exceptional. Northern elephant seal foraging migrations are in the order of 7 500

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km for adult males and 4 800 km for females (Le Boeuf 2000). The migration routes are suspected to pass through areas of apparently unproductive waters to regions of prey concentration (Slip 1994, Stewart and DeLong 1994).

Tracking migrations of marine species has enabled researchers to describe their pelagic distribution in relation to prey and the ocean's physical, chemical and biological structure and variability. Many have focussed on correlating ecological aspects (such as the foraging regions) of the study species with environmental characteristics (eg fur seals, Georges *et al.* 2000; sperm whales, Jaquet and Whitehead 1996; other whales, Tynan 1998; southern elephant seals, Hindell *et al.* 1991a). These data can also be used to assist with the conservation and management of species, in particular threatened species. The spatial and temporal scales at which the two disciplines operate might be quite different. Ecological studies are of fine (tens of km) to meso scale (hundreds of km) resolution in order to correlate the position of the study animal with individual water masses, bathymetry or patches of productivity (Hunt and Schneider 1987, Hunt 1991). In contrast, marine mammals that make lengthy migrations and have wide global distributions could be correlated with macro-scale (>100s of km) features such as fishery regions and the extensive frontal areas of the open ocean. Correlations between species and environmental features have been shown to be scale-dependent (Hunt and Schneider 1987). For example, sperm whale (*Physeter macrocephalus*) sightings are correlated with environmental features and productivity at scales ranging between 80 to 640 nautical miles (Jaquet and Whitehead 1996), approximately 1 to 10 degrees of latitude and longitude. The scale at which these studies can correlate animal position with the ocean's physico-chemical attributes depends in the first instance entirely upon the accuracy of the subjects geographical positioning.

Currently, satellite telemetry and geolocation are two techniques commonly used to track and position the pelagic migrations of marine mammals and sea birds (Wilson 2000), however global positioning system (GPS) units are now being developed (Telonics, 1996). Satellite telemetry uses a powered signal transmission emanating from a platform transmitter terminal (PTT). The PTT transmits signals from the animal at the earth's surface to an ARGOS package attached to earth orbiting National Oceanic and Atmospheric Administration (NOAA) satellites. Messages are then redirected to ground facilities which receive and process data.

The result is the ability to track an individual animal's migration in real time while the observer is remote from the subject. Although capable of giving several, high quality fixes (± 150 m at best) per day, the most prohibitive factors in satellite tracking marine mammals are cost, particularly for studies involving large numbers of individuals, and attachment methods.

Geolocation is an alternative method that uses data collected on light intensity recorded at a predetermined interval over a 24-hour period. The time midway between dawn and dusk, local apparent noon, relative to Universal Time (UT) is used to determine the animals' longitude. Day length (the period between dawn and dusk) determines latitude (Hill 1994). The requirement for latitude positioning is an accurate determination of time of dawn and dusk on a daily basis. Unlike satellite tracking where several locations per day are possible, geolocation can provide at most only two estimates of location in a 24-hour period (Wilson *et al.* 1992); one based on the period of daylight and the other on the period of darkness. Geolocation instruments are inexpensive and thus large numbers of individuals can be tracked in a study making them a useful tool for cross-sectional, longitudinal and long-term studies. Geolocation from archival units returns data only from individuals that can be re-captured for retrieval of the instrument, and thus only animals with successful migrations are available. Data from individuals or recorders that perish at sea are lost.

Geographic position from standard equations for solar navigation using dawn and dusk light levels and time has an at-best accuracy of 130 km for latitude and 120 km for longitude (Wilson *et al.* 1992) or approximately ± 1° of latitude and longitude (Hill 1994). Early calibration supported this (DeLong *et al.* 1992). The actual location of the subject can be anywhere within this range and thus there may be a maximum 2° variation from the location of an animal and its position as estimated by geolocation. Combining the light data with sea-surface temperature readings has been used to improve the accuracy of the locations calculated by geolocation (Le Boeuf 1994). Hill (1994) suggested representing the migrations of seals using the mid-point of the location range should be done for convenience only and that the presentation of error estimates should be plotted using rectangles that indicate the limits of the animals' position to a given level of certainty. So far no published studies have done so.

The accuracy of estimated locations using geolocation also varies at a range of spatial and temporal scales (e.g., season and latitude). DeLong *et al.* (1992) recommended that the influence of latitude and season on the accuracy of estimated positions should be further investigated where GLTDRs are to be deployed on free-ranging animals. For most locations [globally] and most dates, the method can determine location to better than 150 km [approx. 1.3°] half of the time (Wilson *et al.* 1992).

In this study I have documented the influence of latitude and season on the accuracy of geolocation estimates in the region of Macquarie Island (57°35'S, 158°55'E) and to its south. I report confidence limits for the geolocation estimates based on (1) stationary platforms on Macquarie Island in a range of seasons and (2) free-ranging southern elephant seals, with locations simultaneously determined by satellite transmitters in a range of latitudes and seasons. These levels of accuracy reflect spatial scales that may be used by researchers for plotting the positions of marine mammals tracked by geolocation.

3.2 MATERIALS AND METHODS

3.2.1: Stationary Deployments

The land-based stationary site used at Macquarie Island was a viewing platform located at the apex of the "Razorback", a steep-sided low-lying ridge located at the southern end of the isthmus near the Australian National Antarctic Research Expeditions (ANARE) station (Figure 3.1). The Razorback site was chosen because there were no obstacles located between the sun's path and the geographic location-time-depth recorders (GLTDRs) light-level sensor that might influence the times of measured dawn and dusk, as is the case when the seals gather at-sea locations. All seal based deployments were made within a 500 m radius of the platform.

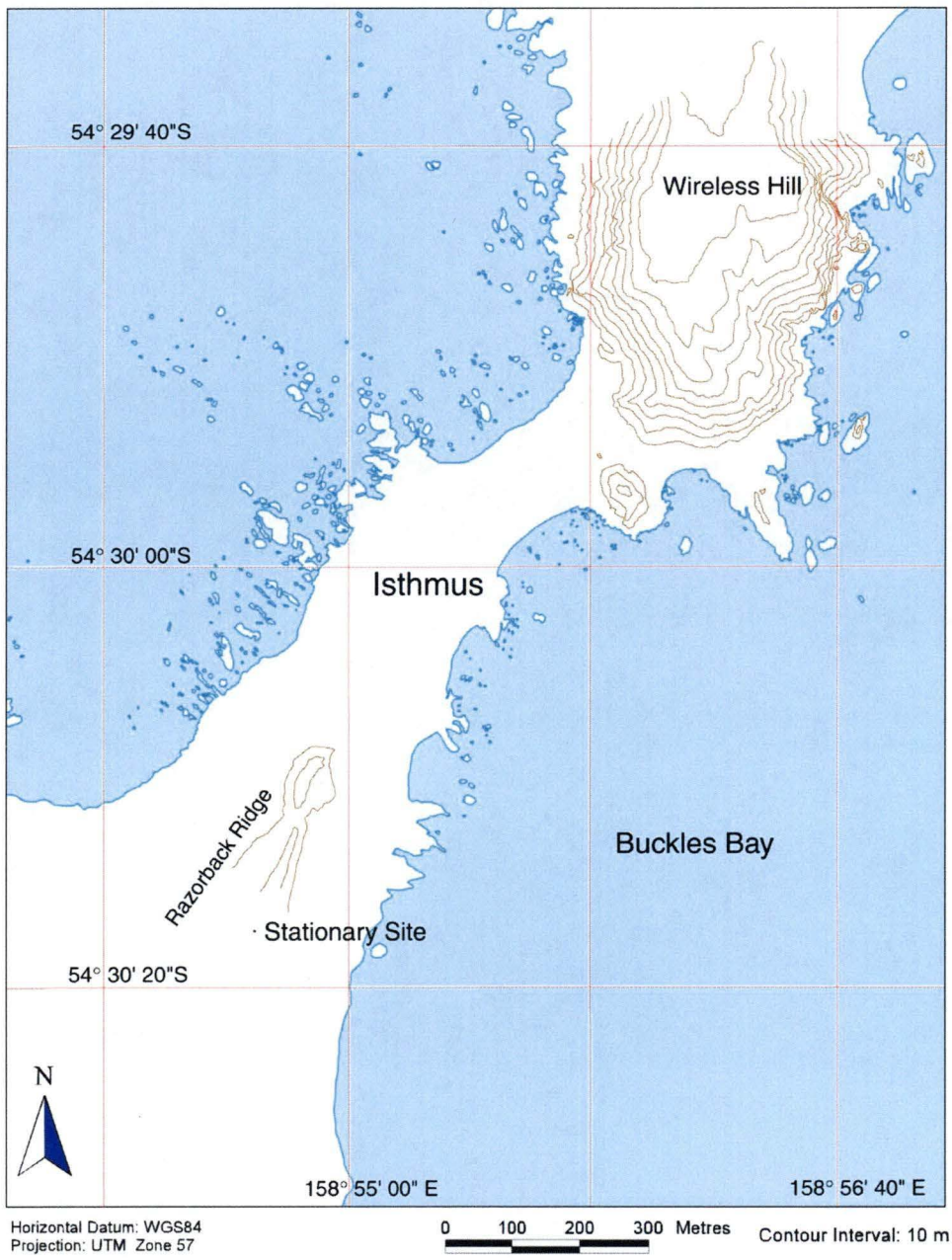

Figure 3.1 Map of the study area (stationary site) located on the low-lying isthmus at Macquarie Island where juvenile seals were captured.

Two deployments were made on the Razorback site, the first used a single Mk3e, two Mk5 and two Mk7 recorders (Wildlife Computers, Redmond, Washington, USA) between 04/August/1998 and 10/August/1998 and the second used six Mk5 recorders between 04/February/1999 and 28/February/1999. Twenty-two recorders, eight Mk3e and 14 Mk5, were also glued to the backs of 22 juvenile (<1 – 2 year-old) southern elephant seals hauled out on the isthmus beaches close to the Razorback.

Of the 22 recorders deployed on juvenile seals, 17 spent between 3 and 16 days on the isthmus at Macquarie Island prior to departure for foraging migrations. Seven recorders were deployed during the 20/August – 15/October equinox period, the remainder were deployed outside the equinoxes. The seals were used as "stationary" sites while they remained hauled out on the beach. In addition, four post-moult male elephant seals, aged five years, were instrumented with both a Mk7 GLTDR and a ST-10 PTT (Telonics Telemetry-Electronics Consultants, Mesa, AZ, U.S.A.). One of these seals was used to determine the error between geolocation and satellite location fixes.

The geographic location of the Razorback site at Macquarie Island was determined with a Garmin GPS 12 accurate to approximately 100 meters (Dana 1999). Geolocation TDRs deployed on five year-old male southern elephant seals were truthed against an accompanying ST-10 PTT using the best near noon location class for a particular day.

3.2.2: Instrument Protocols, Data Retrieval and Analysis: Stationary Deployments

Shore-based GLTDR deployments logged light for 120 seconds at a period of 20 minutes. Upon retrieval, the recorded hexadecimal data were saved to a personal computer. Wildlife Computers GEOLOCATION analysis software version 2 was used to estimate geographic location of Mk3e and Mk5 GLTDRs from the stored hexa-decimal files. Each file was manually checked and the resulting light-level curves smoothed by deleting obvious perturbations (dips and spikes), particularly if these coincided with temperature fluctuations and seal behavior such as rolling on the GLTDR. Perturbations in the pre-dawn and post-dusk baseline and the dawn-rise and dusk-set curve were also deleted. The smoothed curves were then used by

the GEOLOCATION software to estimate dawn-dusk (DD) times from which an algorithm calculated approximate geographic location (Hill 1994). From light-level readings one location, given as decimal degrees latitude and longitude, was estimated per 24-hour period.

For the Mk7 GLTDRs, a different program, Multitrace (Jensen Software) was used to estimate the sunrise and sunset times for calculation of latitudes and longitudes. The program does not give an estimate of the range of possible locations, using only the midpoint of likely positions. It does however, provide two locations per 24-hour period.

Atmospheric pressure, temperature and cloud conditions for the period of the February 1999 deployment were obtained from a meteorological station located on the isthmus of Macquarie Island.

Distance between the Razorback location and stationary GLTDRs were calculated as the radius length (great circle distance) between the known location and range of estimates for the geolocation of that site. Radial errors were then plotted as the cumulative percentage of these deviations in 0.1 decimal degree increments for the deployment period. The 95^{th} and 68^{th} percentiles were selected for tabulating the data.

3.2.3: At-Sea Deployments

Southern elephant seals were captured and an intravenous injection of ketamine (2.0 - 3.0 mg/kg) and diazepam (0.05 - 0.2 mg/kg) (Slip and Woods 1996) or Zoletil 100 (Virbac, Australia) (McMahon *et al.* 2000a) anaesthetised the seals while they were marked and the tracking instruments attached.

Archival Wildlife Computers GLTDRs and VHF transmitters (Advanced Telemetry Systems, Minnesota, USA) were attached with epoxy glue (Araldite K268, Ciba-Geigy) to the dorsal mid-line, approximately 60 cm from the tip of the nose of the seals. Pressure housed (Sirtrack, Havelock North, NZ) satellite transmitters (Telonics ST-10) measuring 6.0 X 15.0 X 4.0 cm and weighing 480 g were glued directly to the hair on top of the study seal's head. The 16 cm antenna

was angled forward at 45° so that the maximum number of transmissions could be made while the seal was at the surface.

3.2.4: Instrument Protocols, Data Retrieval and Analysis: At-sea Deployments

Each Mk7 GLTDR (Wildlife Computers) was programmed to store continuous measurements of light and sea temperature in memory. The Mk7 data were analysed using Multitrace (see above). Spatial and temporal variation in Mk7 GLTDR error was established by comparing the Multitrace locations with daily satellite established positions before and after the geolocations were filtered (McConnell and Fedak 1996).

Southern elephant seals dive continuously while at sea, with inter-dive surface intervals ranging from 2.1 – 4.1 minutes and dives lasting between 16 – 37 minutes on average (Slip *et al.* 1994). Each ST-10 PTT was pre-programmed to continuously transmit a signal every 40 seconds when the seal surfaced. A salt-water switch was incorporated into the PTT housing to preserve the battery voltage while the seal submerged.

One seal (B284) made two pelagic migrations during the deployment period with the PTT attached to his head. While hauled-out at Macquarie Island between foraging trips, the PTT continued transmitting locations of variable quality (= location quality or LQ). Argos predicts the accuracy of locations is ≤ 150 m for LQ3, 150 - 350 m for LQ2, 350 – 1 000 m for LQ1 and > 1 000 m for LQ0 (ARGOS, 1998). The accuracy of the locations is dependent on the number of uplinks received from the transmitter attached to the seal because the position of the seal is calculated from the Doppler shift in frequency occurring during the satellites orbit (Taillade 1992).

While seal B284 was ashore, the accuracy of each LQ received was determined by comparing each satellite position with a known grid reference within which the seal was resighted during his haulout in July. The "true" location of the seal was assumed to be in the centre of the coastline, approximately 1-km long, which passes through the grid.

At-sea PTT transmitted locations and Mk7 GLTDR stored locations were compared for the four male seals aged five years. The locations were established and the great circle distance between the location types was measured to determine the radial error. The cumulative percent of radial errors between the GLTDR and PTT were plotted in 5°S latitudinal bins for the deployment period.

During migration, elephant seals are capable of horizontal travel rates in the range of 100 – 220 km.day^{-1} depending on sex and breeding cycle (Slip 1997, Le Boeuf 2000). Thus to remove locations with potential error, due to poor dawn – dusk timing for example, each geolocation file was run through an iterative forward/backward averaging filter (McConnell *et al.* 1992a). Both filtered and unfiltered geolocations were plotted to display the differences between the two.

3.2.5: Spatial and Temporal Variation

The influence of time of year (equinox and non-equinox periods) on the accuracy of a stationary deployment was investigated for all stationary and at-sea deployments. This was achieved by placing the geolocation estimates into weekly bins and determining the radial error as above.

3.2.6: Statistical Analyses

A paired *t*-Test was used to test for between GLTDR differences in location estimation of the Razorback site. Stepwise multiple regression was used to correlate weather parameters with geolocation estimates for the Razorback site during February 1999. A value with $P \leq 0.05$ denoted a significant difference throughout.

3.3 RESULTS

3.3.1: Stationary Deployments

Time-depth recorders deployed at the Razorback, Macquarie Island, logged light between 04/August - 10/August/1998 and 05/February - 28/February/1999. Both deployment times fell outside equinox periods, although the February deployment did end one day into an equinox period (27/February to 21/April, Wildlife Computers 1993). Seventeen of the juvenile seals fitted with either a Mk3 or Mk5 unit stayed on-shore and logged light for more than three days. Ten of these units logged light outside equinox periods while 7 logged during equinox times.

3.3.2: August 1998 Deployment

The GPS location of the Razorback site fell at the edge of the probable mean geographic area estimated from all three TDRs (coloured box in Figure 3.2). When the locations derived from the individual TDRs were compared, there was no statistically significant difference between TDR estimation of longitude, but there was a difference in latitude estimation (91-1728 vs 91-021, Table 3.1).

During August 1998, the most distant location estimate was 397 km north-east of the study site (TDR No. 91-1728) (Figure 3.2). Ninety-five percent of all location estimates were within a 3.9° radial distance of the Razorback site (Figure 3.3a). Sixty-eight percent (the equivalent to ± 1 standard deviation.) of locations were within a 1.4° radial distance (Figure 3.3a).

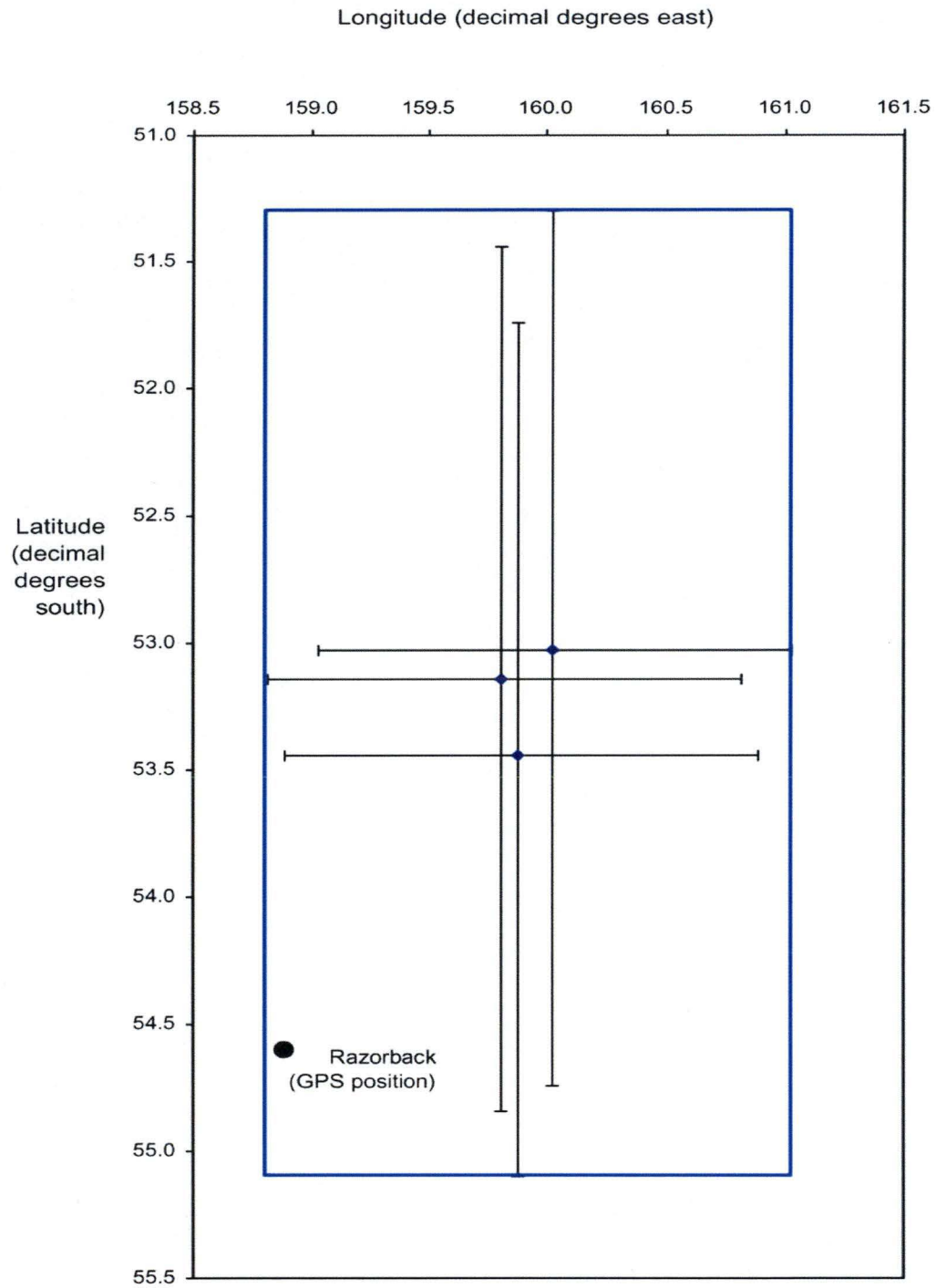

Figure 3.2: Range of geolocation estimates (blue box) for the GLTDRs deployed between 4 – 10 August 1998. The GPS location for the Razorback at Macquarie Island is shown.

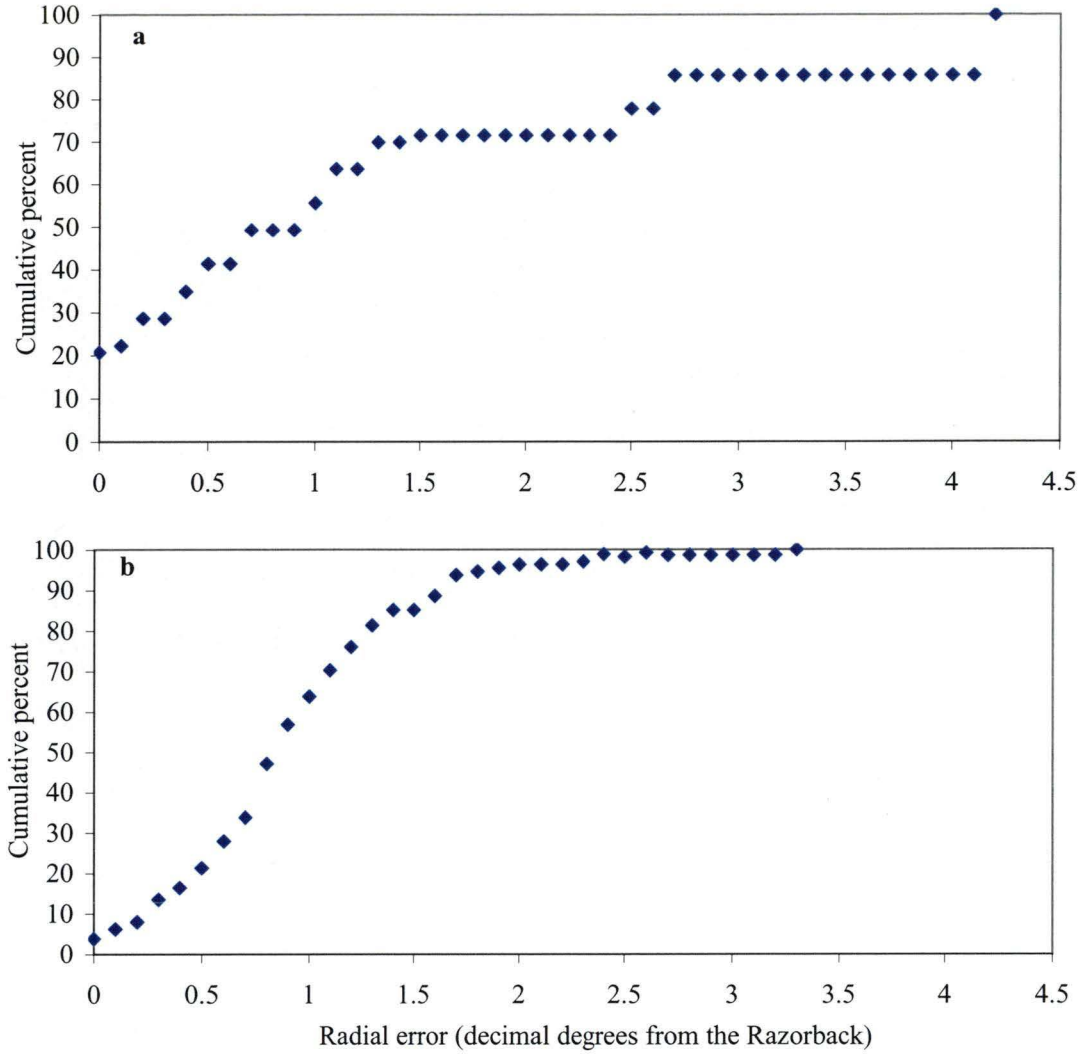

Figure 3.3: Cumulative percentage in 0.1° increments for the radial error in geolocation estimates of the Razorback site at Macquarie Island during August 1998 (a) and February 1999 (b).

Table 3.1: Paired sample *t*-Test results for between GLTDR comparisons of latitude and longitude estimation during August 1998 at the Razorback, Macquarie Island. * = significant difference, SE = standard error, MoM = Mean of Means

	TDR	Mean ± SE	TDR comparison	*t*-Statistic	$P_{(02, 6)}$ value
Longitude	91-1728	159.97 ± 0.39	91-1728 vs 91-021	1.11	0.31
			91-1728 vs 91-030	1.30	0.24
			91-1728 vs MoM	1.76	0.13
	91-021	159.88 ± 0.42	91-021 vs 91-030	-0.67	0.53
	91-030	159.80 ± 0.47	91-021 vs MoM	-0.39	0.71
	MoM	160.03 ± 0.40	91-030 vs MoM	-1.09	0.32
Latitude	91-1728	52.97 ± 0.97	91-1728 vs 91-021	-3.19	0.02*
			91-1728 vs 91-030	-0.68	0.53
			91-1728 vs MoM	-2.35	0.06
	91-021	53.44 ± 0.97	91-021 vs 91-030	-1.29	0.24
			91-021 vs MoM	2.23	0.07
	91-030	53.11 ± 1.01	91-030 vs MoM	-0.42	0.69

3.3.3: February 1999 Deployment

The GPS location of the Razorback site fell within the mean geographic area estimated by geolocation (coloured box in Figure 3.4). There was between GLTDR variability in the estimation of latitude for the Razorback; recorders 91-030, 91-031 and 91-032 gave similar estimates, while 91-029 and 91-044 also gave similar estimates to each other but different to the other instruments. Unit 91-034 was significantly different to all other instruments (Table 3.2 a). Units 91-029, 91-034 and 91-044 all significantly differed from the mean of means (Table 3.2 a). There was one statistically significant difference in the GLTDRs estimation of longitude (91-034 vs 91-044, Table 3.2 b) but neither instrument differed from the mean of the means, nor from any other GLTDR.

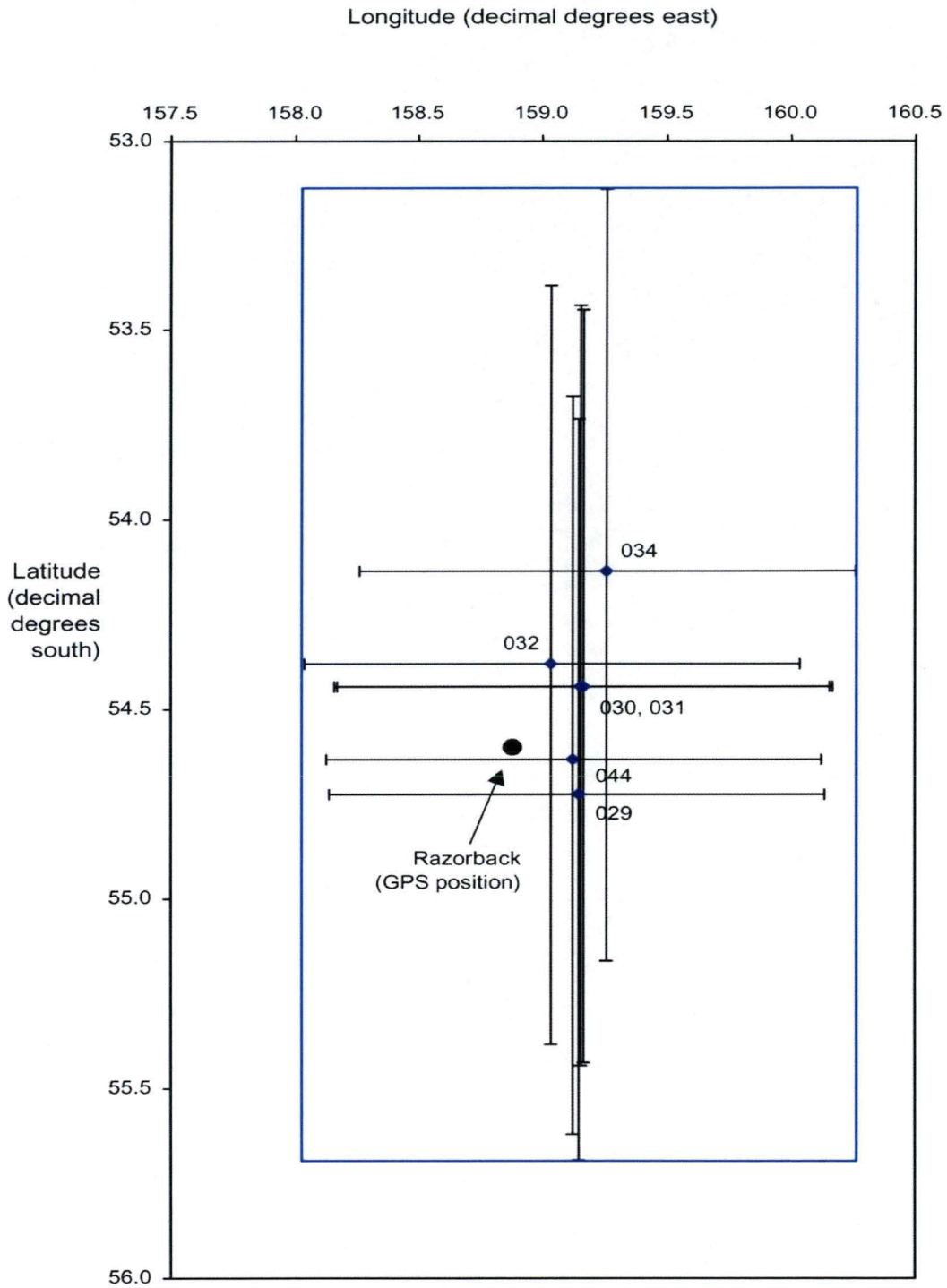

Figure 3.4: Range of geolocation estimates (blue box) for the GLTDRs deployed between 04 – 28 February 1999. The GPS location for the Razorback is shown.

The most distant location estimate was 187 km north-east of the study site (TDR No. 91-034, Figure 3.4). During the 25 deployment days in February 1999, the estimated position of the Razorback varied on a daily basis (Figure 3.5a). The worst estimates of latitude were recorded on 14/February/1999 (419 km north) and 25/February/1999 (294 km south, Figure 3.5 b). Worst estimates of longitude were 195-km east and 158 km west on 22/February/1999 and 20/February/1999, respectively (Figure 3.5c).

Ninety-five percent of all location estimates were within a 1.9° radial distance of the Razorback site and sixty-eight percent of locations were within a 1.1° radial distance (Figure 3.3b).

Table 3.2a: Paired sample *t*-Test results for between GLTDR comparisons of latitude estimation of the Razorback at Macquarie Island, during February 1999. * = significant difference, SE = standard error, MoM = Mean of Means

TDR No	Mean latitude ± SE	TDR comparison	*t*-Statistic	$P_{(02, 24)}$ value
91-029	54.74 ± 0.22	91-029 vs 91-030	4.80	<<0.001*
		91-029 vs 91-031	2.64	0.014*
		91-029 vs 91-032	3.71	0.001*
		91-029 vs 91-034	11.38	<<0.001*
		91-029 vs 91-044	1.71	0.101
		91-029 vs MoM	5.50	<<0.001*
91-030	54.44 ± 0.22	91-030 vs 91-031	0.00	1.00
		91-030 vs 91-032	0.72	0.47
		91-030 vs 91-034	4.24	<<0.001*
		91-030 vs 91-044	-4.44	<<0.001*
		91-030 vs MoM	-0.61	0.55
91-031	54.44 ± 0.23	91-031 vs 91-032	0.67	0.51
		91-031 vs 91-034	2.65	0.014*
		91-031 vs 91-044	-2.15	0.042*
		91-031 vs MoM	-0.29	0.772
91-032	54.38 ± 0.20	91-032 vs 91-034	2.40	0.025*
		91-032 vs 91-044	-2.77	0.01*
		91-032 vs MoM	-1.27	0.22
91-034	54.15 ± 0.23	91-034 vs 91-044	-7.73	<<0.001*
91-044	54.63 ± 0.21	91-034 vs MoM	-5.96	<<0.001*
MoM	54.46 ± 0.21	91-044 vs MoM	4.53	<<0.001*

Table 3.2b: Paired sample *t*-Test results for between GLTDR comparisons of longitude estimation of the Razorback at Macquarie Island, during February 1999. * = significant difference, SE = standard error, MoM = Mean of Means

TDR No	Mean longitude ± SE	TDR comparison	*t*-Statistic	$P_{(02, 24)}$ value
91-029	159.16 ± 0.18	91-029 vs 91-030	-0.10	0.92
		91-029 vs 91-031	0.04	0.97
		91-029 vs 91-032	1.36	0.19
		91-029 vs 91-034	-1.75	0.09
		91-029 vs 91-044	0.60	0.55
		91-029 vs MoM	0.23	0.82
91-030	159.16 ± 0.22	91-030 vs 91-031	0.18	0.86
		91-030 vs 91-032	1.31	0.20
		91-030 vs 91-034	-1.03	0.31
		91-030 vs 91-044	0.67	0.51
		91-030 vs MoM	0.37	0.71
91-031	158.16 ± 0.21	91-031 vs 91-032	1.16	0.26
		91-031 vs 91-034	-0.94	0.36
		91-031 vs 91-044	0.33	0.75
		91-031 vs MoM	0.08	0.94
91-032	159.04 ± 0.21	91-032 vs 91-034	-1.84	0.08
		91-032 vs 91-044	-0.84	0.41
		91-032 vs MoM	-1.49	0.15
91-034	159.26 ± 0.20	91-034 vs 91-044	2.21	0.04*
91-044	159.12 ± 0.21	91-034 vs MoM	1.79	0.09
MoM	159.15 ± 0.20	91-044 vs MoM	-0.59	0.56

A stepwise multiple regression was used to test for the effect of local weather patterns on geolocation accuracy. The relationship between radial error in location and the following variables was investigated: the difference between maximum and minimum daily temperature, the difference in maximum and minimum temperature measured by the TDR, cloud cover (binary – 0 = low cloud, octaves 1 - 5; 1 = high cloud, octaves 6 - 8), and atmospheric pressure. The regression did not exclude any variables from the model; however, only two variables suggested a possible relationship to radial location error, they were atmospheric pressure ($t_{(24)} = 2.14$, $P = 0.044$) and cloud cover ($t_{(24)} = 1.82$, $P = 0.084$). However, error variances were not homogeneous, and the full model was not significant. This suggests that either there was not enough power to detect an effect of these variables on radial error, or that the observed effects were weak.

3.3.4: Comparison within Non-Equinox Periods

The difference in geolocation estimates between months was examined within two non-equinox periods. I compared the first seven days of the August 1998 and the first seven days of February 1999 deployments. The difference between the mean estimates for longitude was 0.73° (1998 = 159.88°E, 1999 = 159.16°E, $t = 1.03$, $P_{(6)} = 0.34$). Similarly, a difference of 1.01° in estimates of latitude were not statistically different (1998 = 53.18°S, 1999 = 54.19°S, $t = 1.15$, $P_{(6)} = 0.29$).

3.3.5: Juvenile Southern Elephant Seal Deployments

The estimation of geographic location during equinox and non-equinox periods for juvenile seals hauled out on the isthmus is shown in Figure 3.6a and b. In both cases the location of the Razorback, taken to represent the seals' location, was within the mean area predicted from all the GLTDRs within the deployment but there was considerable variation in the individual TDR estimates, particularly during the equinox. Ninety-five percent of all location estimates during the equinox deployments were between 12 - 21° radial error of the Razorback site and sixty-eight percent of locations were within a 6.7° radial distance (Figure 3.7a). During the non-equinox periods ninety-five percent of all location estimates were within a 3.3° radial distance of the Razorback site and sixty-eight percent of locations were within a 1.4° radial distance (Figure 3.3b).

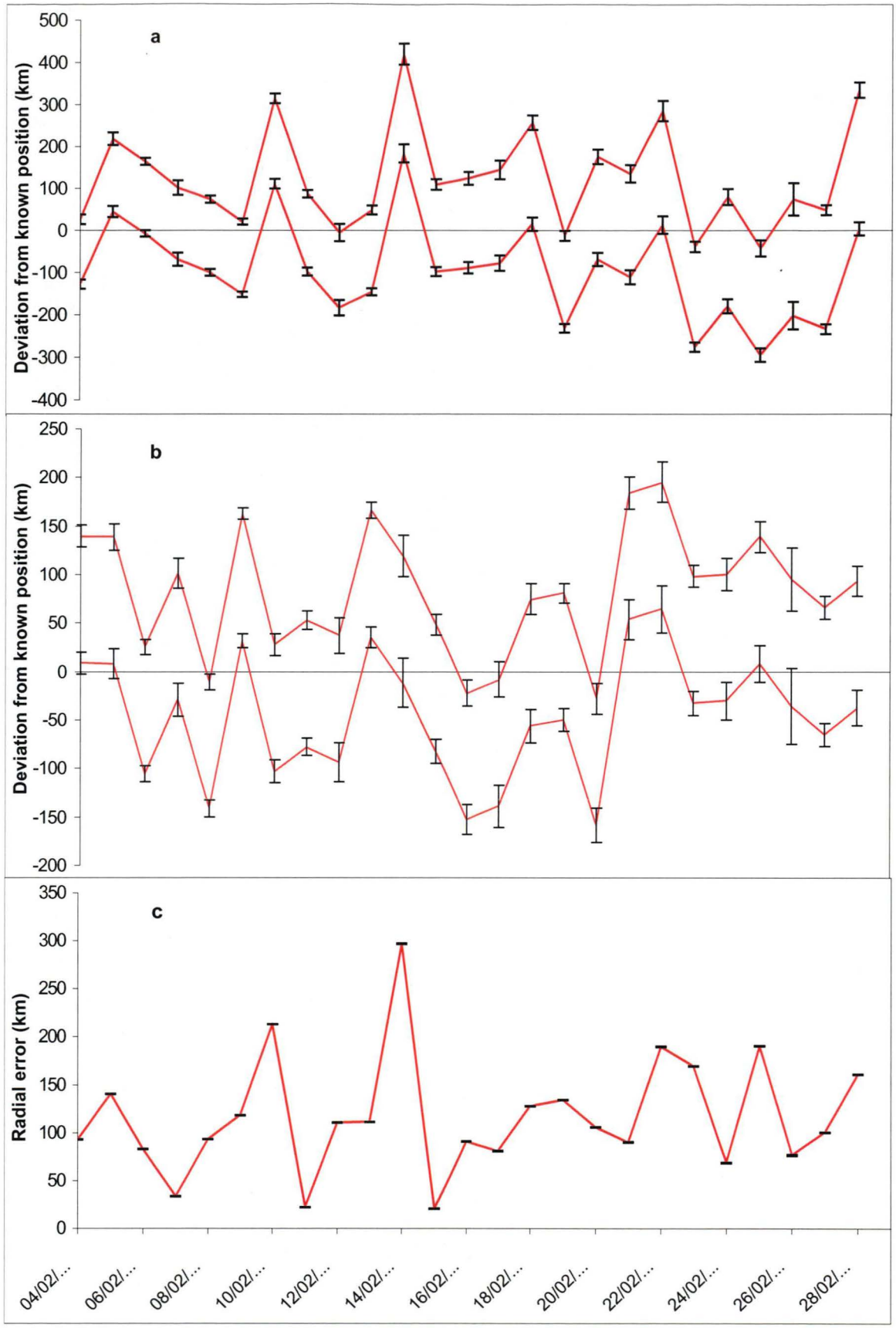

Figure 3.5: Daily variation in estimates of (a) latitude (b) longitude, and (c) radial error for the Razorback at Macquarie Island between 04–28 February. 1999. Bar = SE

3.3.6: Intra-Annual and Latitudinal Variation in Location Estimation at the Stationary Site

All stationary and juvenile seal TDR estimates for the location of the Razorback gathered during this study were pooled to assess the temporal variation in TDR estimation of location. Estimates for the location of the Razorback at Macquarie Island were gathered for 23 weeks of the year (Figure 3.8). Deployments covered both equinox and non-equinox periods. The best estimates of location were recorded during non-equinox periods, particularly in February and December (Figure 3.8). The 68^{th} and 95^{th} percentiles of the radial distance between the Razorback and the geolocation estimates for equinox and non-equinox periods are shown in Table 3.3.

3.3.7: At-Sea Deployments

The PTT deployed on seal B284 produced 164 locations of all possible location qualities (LQs) over the 39 days he was ashore on Macquarie Island during July 1999 (Figure 3.9). Sixty-two percent of the locations were of LQ class 1 or better.

Analysis of variance of the LQs indicated there were significant differences between the mean distance each LQ was from an other (ANOVA: F – ratio = 8.79, $df = 5$, $P = 0.000$; Figure 3.10). A Tukey Post Hoc test showed LQs 1, 2 and 3 were not significantly different from each other but LQ0, LQA and LQB were all different to LQ1 and LQ2 but not LQ3 (Table 3.4). At-sea location error for the PTT could not be calculated because there were no reference points against which to calculate the PTT location. The at-sea LQs were dominated by class A and B hits with LQ B the most numerous (Table 3.5). Therefore the comparison between the PTT and the geolocation estimate of at-sea location was restricted to PTT LQ A and B hits only. The average error between an LQB and a "true" geolocation (ie. one in exactly the correct position) might still deviate 32 km (Table 3.4).

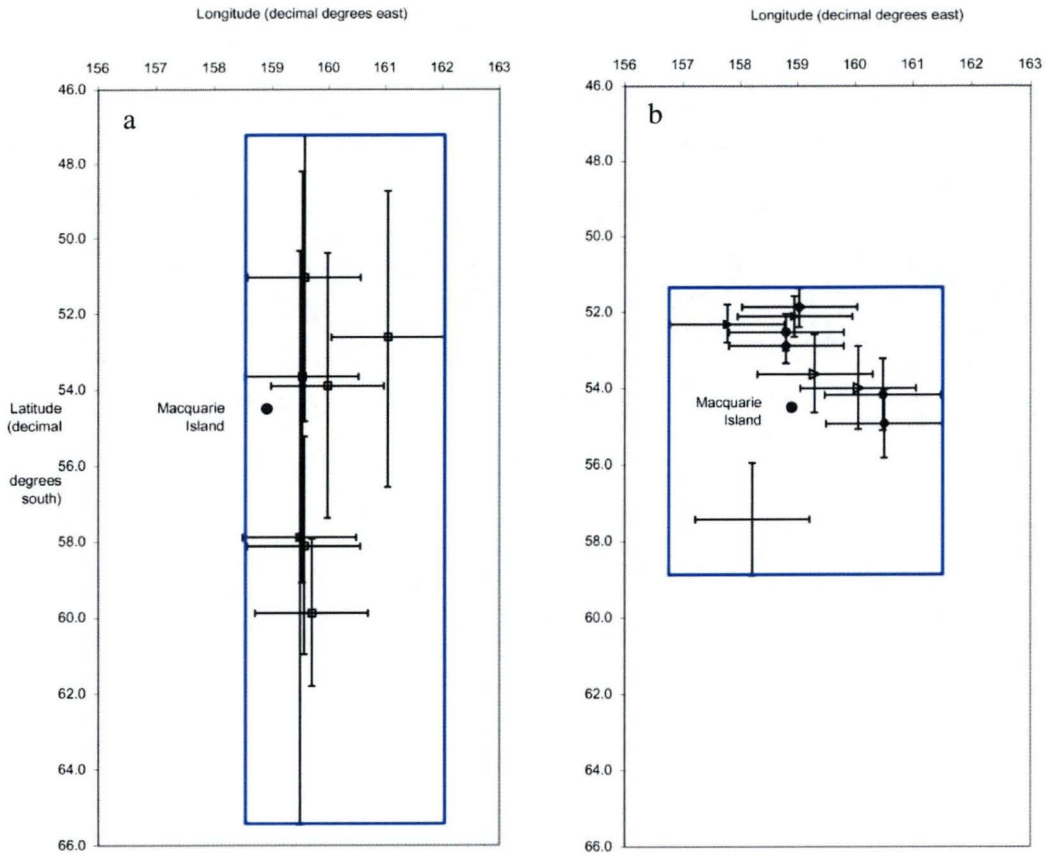

Figure 3.6: Range of geolocation estimates (black box) for the GLTDRs deployed on juvenile seals at Macquarie Island. The GPS location for the Razorback is shown. a = with equinox periods. b = non-equinox periods.

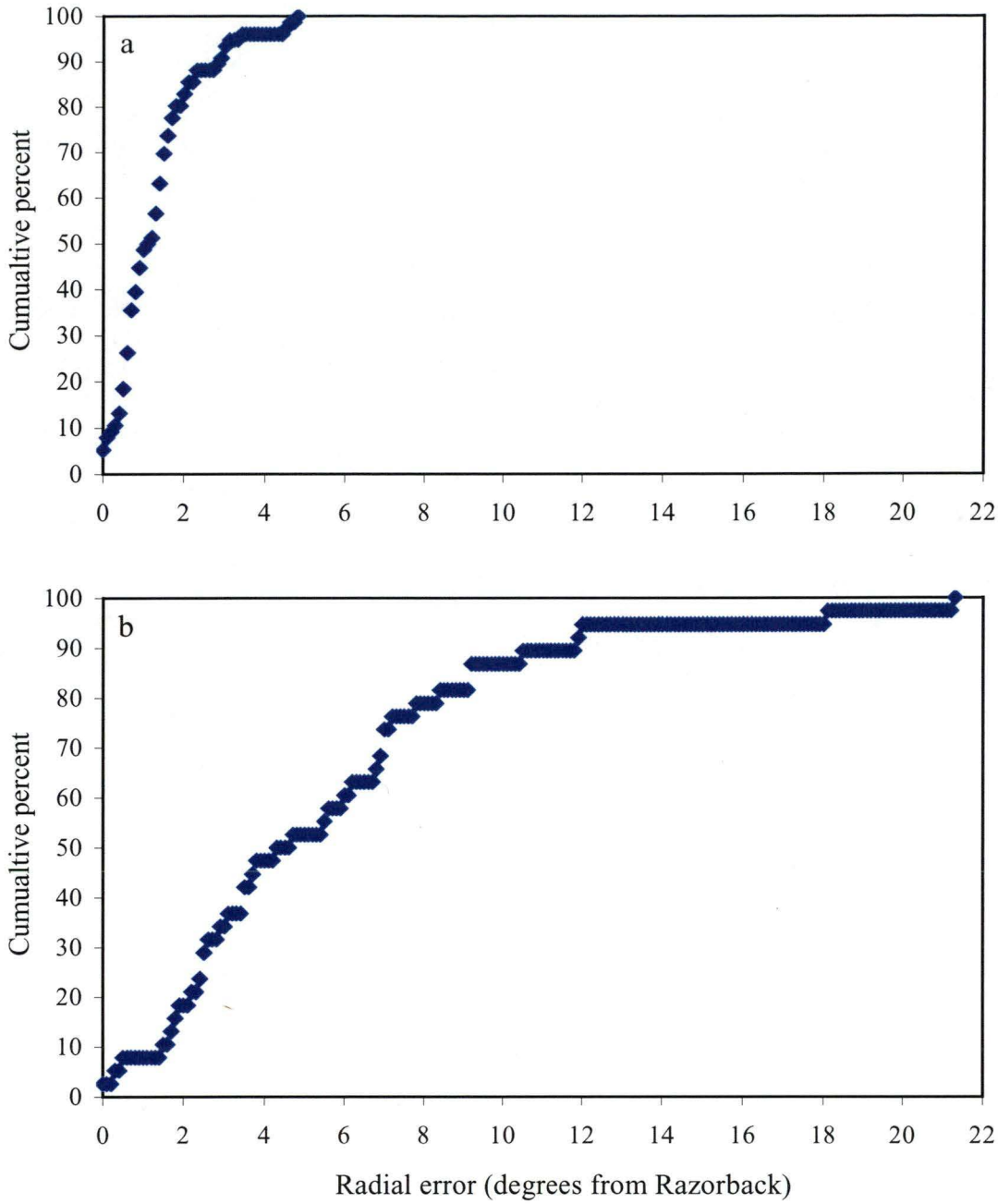

Figure 3.7: Cumulative percentage of 0.1° increments of radial error in geolocation estimates for the locations of juvenile elephant seals at Macquarie Island during non-equinox (a) and equinox (b) periods.

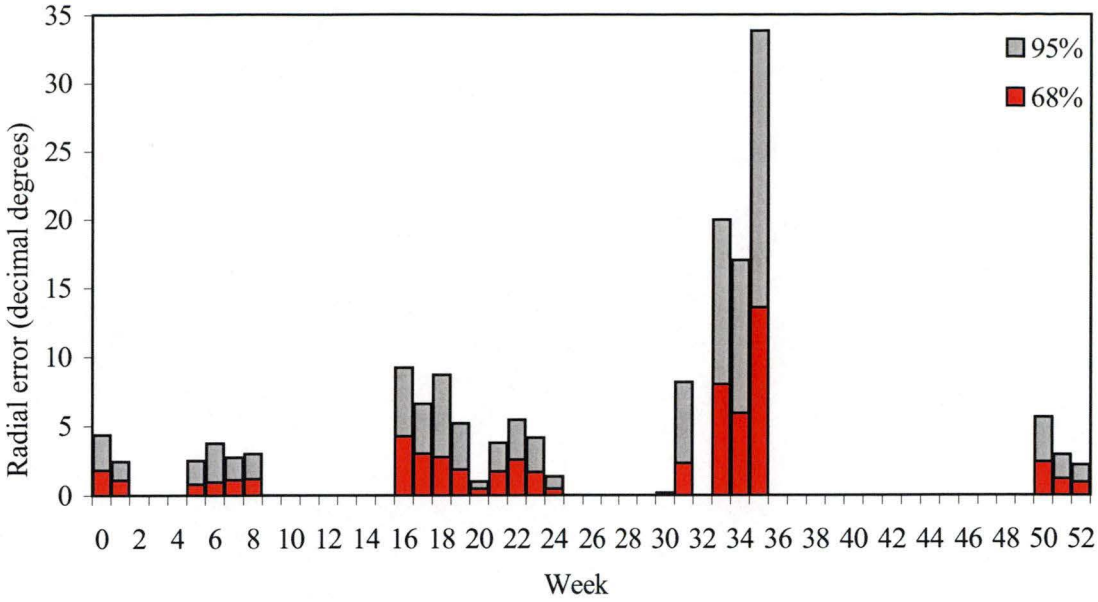

Figure 3.8: Weekly variation in radial error for the geolocation of the Razorback at Macquarie Island during all on-shore TDR deployments. 68th and 95th percentiles shown. Bin 0 = first week, Bin 1 = second week etc.

Table 3.3: Radial distance (Mean ± SE in decimal degrees) within which 68% and 95% of the Razorback locations were found during all shore-based deployments.

Period	68 %	95%
Equinox	7.92 ± 2.34	12.08 ± 3.63
Non-equinox	1.47 ± 0.22	2.42 ± 0.41

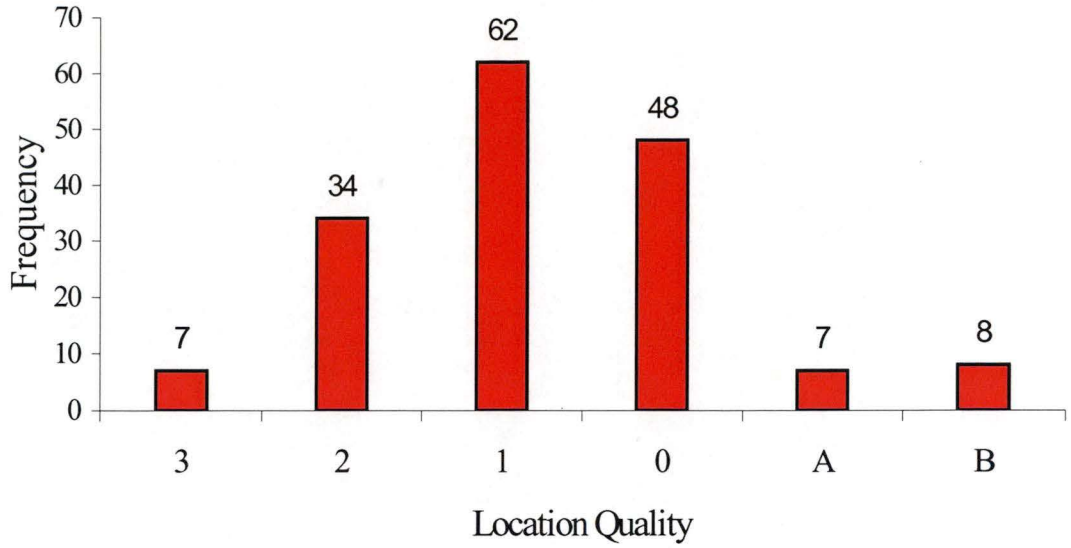

Figure 3.9: Frequency distribution of LQs received from seal B284 while ashore on Macquarie Island in July 1999. Numbers at the head of the bar are the sample sizes.

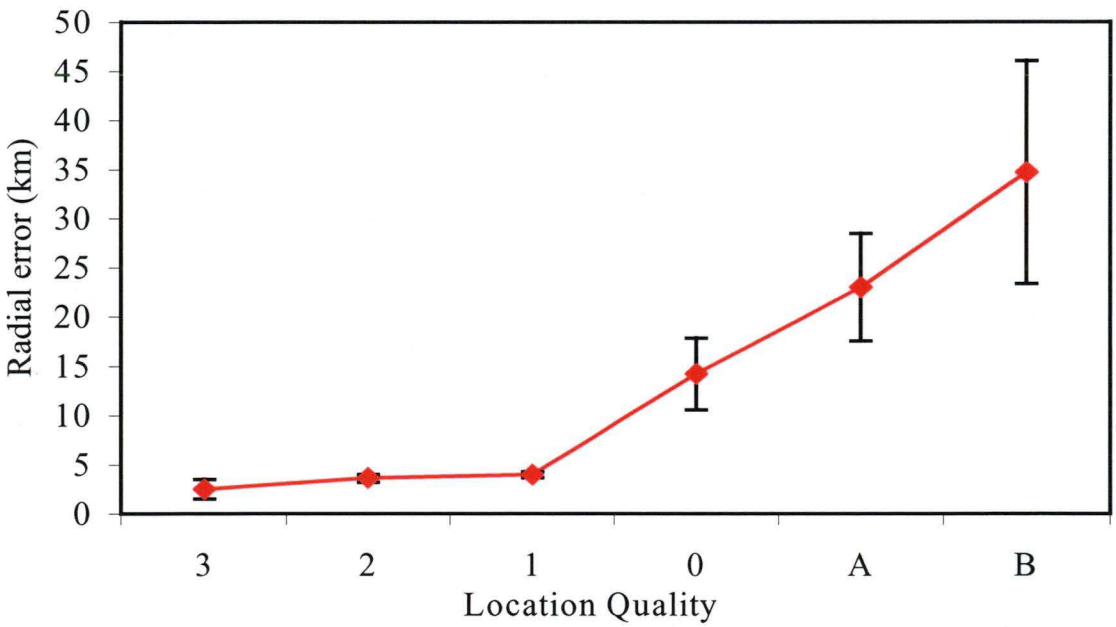

Figure 3.10 Radial error (± SE) in location quality of the ST-10 satellite transmitters while seal B284 was ashore for 39 days during July 1999 on the isthmus at Macquarie Island.

Table 3.4: Relationship between location qualities (LQs) and mean distance between LQs collected by elephant seal B284 while ashore at Macquarie Island. * denotes statistically significant difference.

			Distance (km) between LQs	
Model	Tukey statistic	*P* value	LQs	Distance (km)
3x2	1.11	1.000	3 – 2	1.10
3x1	1.49	1.000	3 – 1	1.47
2x1	0.39	1.000	3 – 0	11.70
0x3	11.70	0.435	3 – A	20.51
0x2	10.59	0.030*	3 – B	32.21
0x1	10.21	0.009*		
Ax0	8.80	0.733		
Ax1	19.01	0.028*		
Ax2	19.40	0.034*		
Ax3	20.51	0.139		
AxB	11.69	0.700		
Bx0	20.50	0.008*		
Bx1	30.70	0.000*		
Bx2	31.09	0.000*		
Bx3	32.02	0.001*		

Table 3.5: Number and percent occurrence of uplinks in each location quality (LQ) while seal B284 was at sea.

LQ	Number and percent occurrence
3	0
2	9 (2.0)
1	20 (4.5)
0	26 (6.0)
A	155 (35.2)
B	230 (52.3)

Three of the four 5-year-old male seals migrated between 54°S and 77°S in the Ross Sea; the remaining seal travelled south-west to the Dumont D'Urville area, reaching latitudes of near 65°S. Their travel was directed to foraging areas where they remained relatively stationary for lengthy periods. The longitude range for the four seals was between 130°E to 170°W. The deployment period, extending from week 1 to week 27 of the calendar year, gave the opportunity to assess error in geolocation relative to the PTT over time. Generally, filtered locations were closer to the PTT location and filtering removed the very worst of the geolocation estimates (Figure 3.11). Estimates were poorer in latitude bins 50-55°S and 55-60°S than in bin 60-65°S during similar times and seasons. The mean radial error between the PTT and Mk7 GLTDR was least between 60–65°S in non-equinox periods (Table 3.6).

Table 3.6: Mean radial error (decimal degrees) between PTT and Mk7 locations.

	Unfiltered locations		Filtered locations	
Latitude bin	Equinox	Non-equinox	Equinox	Non-equinox
50-55°S	13.6	3.17	7.29	2.67
55-60°S		4.91		3.86
60-65°S		6.88		2.07

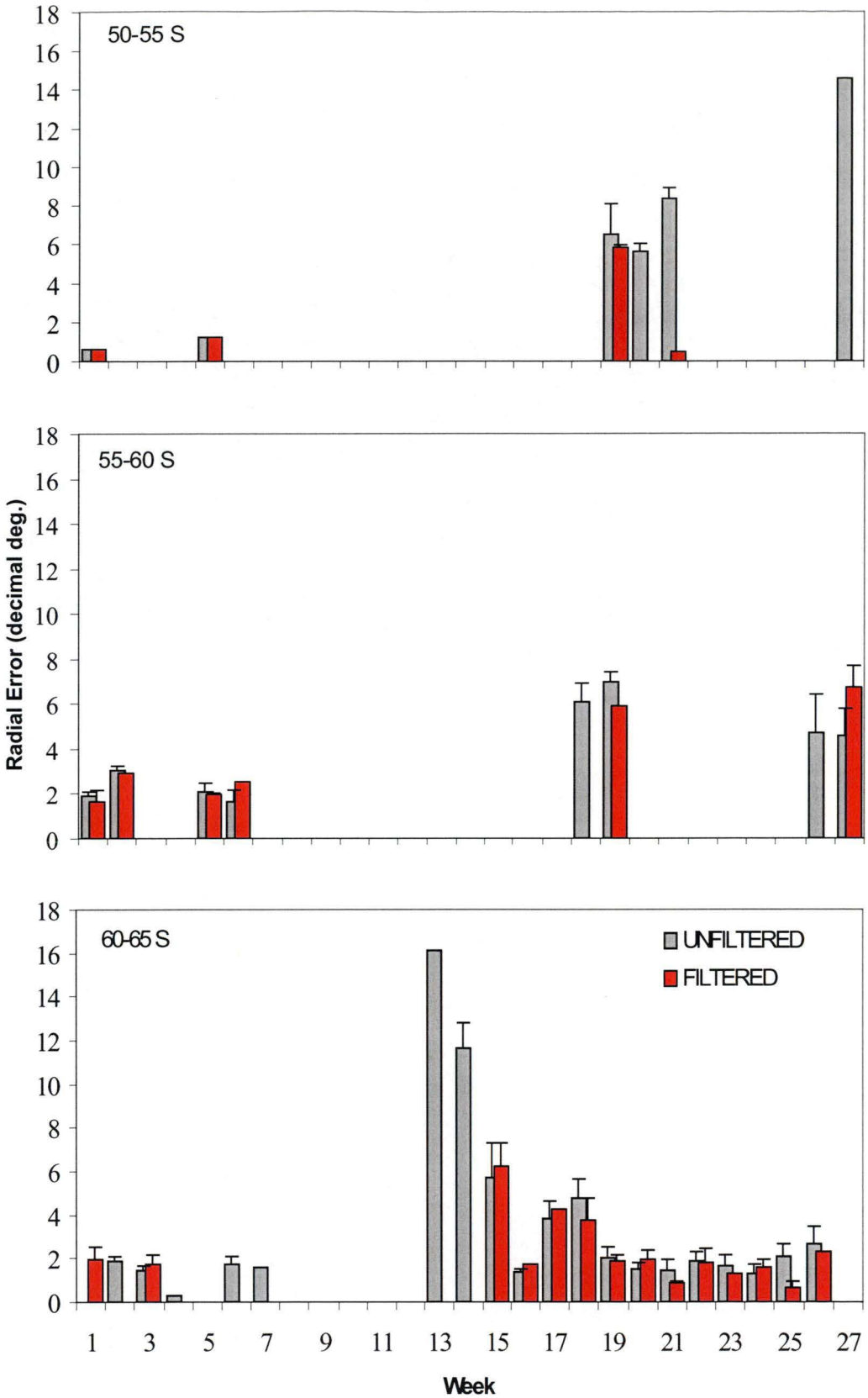

Figure 3.11: Radial error between the filtered and unfiltered Mk7 geolocation estimates and PTT locations (LQ A and B) gathered by five year-old elephant seals from Macquarie Island. Bar = standard error

3.4 DISCUSSION

3.4.1: General Findings in Relation to Previous Studies

DeLong *et al.* (1992), Wilson *et al.* (1992) and Hill (1994) made calibrated and theoretical estimates for the error associated with at-sea geolocation of elephant seals. Their studies reported an "at best" estimate could be within ± 1° (a maximum error of 2°) of the actual location during non-equinox periods, but there was variability in the accuracy of latitude calculation depending on the subjects latitude and the season. Thus, the day length and general location (latitude) affect latitude estimation (Wildlife Computers 1993, Wilson *et al.* 1992). Best locations are recorded during periods when day length is different throughout the world (ie non-equinox times) and at polar latitudes where the rate of change in day length is greater than near the equator (at least when there is a day and night cycle at the pole) (Wildlife Computers 1993). Longitude estimates were found unaffected by season or general location because longitude is calculated from the mid-point between the dawn and dusk (noon) curve relative to a fixed point; universal time. The effect of season and general location upon the accuracy of on-shore and at-sea geolocations during this study can be seen in figures 3.8 and 3.11. The more southerly geolocations of an elephant seal fitted with both a PTT and GLTDR had the best accuracy as predicted by previous workers. Equinox periods produced the worst estimates for on-shore locations.

Location estimation by Wildlife Computers GEOLOCATION software is enhanced by smoothing the dawn - dusk curves first produced from the hexi-decimal file output. Anomalous readings (spikes and dips) can be generated by dramatic changes in temperature, sensor shading by cloud cover and seal behavior; and atmospheric refraction due to temperature and pressure changes (Wildlife Computers 1993). There was considerable variation in daily estimates of location at the Razorback site during a non-equinox period in February (Figure 3.5). Analysis of climate variables collected concurrent with light levels for geolocation showed that there was an effect of air pressure on the magnitude of radial error. Statistically, cloud cover was insignificant. Both pressure and cloud can be accounted for in the GEOLOCATION software when calculating location. All curves were adjusted for known pressure at the study site and the removal of perturbations in the dawn/dusk light slopes was used to account for any effect cloud cover or shading might have. Air pressure is more difficult to account for while an animal is at-sea since the

researcher has no notion of where the study animal has gone and so cannot correct for pressure in the first instance. A standard value would be used and then the analysis re-run with pressure corrected for using known pressure values at specific latitudes and season.

After each TDR was treated identically during deployment, down-loading and analysis, I found between GLTDR differences in the estimation of location (Tables 2 a and b). The differences were statistically significant for latitude but not longitude indicating a high level of precision in the GLTDRs and the software's ability to estimate the time of local apparent noon. This is critical if the user wishes to correct latitude with other factors such as depth in relation to bathymetry, wet/dry times related to haulout periods and sea-surface temperature for comparison with remote sensing data. The between GLTDR differences found in this study for estimating the latitudinal position of Macquarie Island introduces further uncertainty associated with geolocation as a tool for tracking marine mammals.

3.4.2: Stationary Deployments

During this study period, the known location of a stationary site at sub-Antarctic Macquarie Island was within the mean range determined by GLTDRs during two non-equinox periods, August (Figure 3.2) and February (Figure 3.4). In 1992, Wilson *et al.* reported that "for most locations [globally] and most dates, the method (geolocation) can determine location to better than 150 km (approx. 1.3°) half of the time". Ninety-five percent (95 %) of all locations estimated in this study fell within a radial distance of 2.4° during non-equinox and 12.1° during equinox periods. These values are more than twice the error often reported for the accuracy of geolocation but in this case the probability of the study subject being within the area is high. Lesser degrees of certainty (up to 68 %) for locations were within ± 1.5° and ± 7.9° during the same non-equinox and equinox periods.

There was temporal variation in the accuracy of locations as Hill (1994) showed in his study. Here, 68% of the stationary Razorback Ridge locations were within a mean radial distance of 1.47° ± 0.22° in non-equinox periods and 7.92° ± 2.34° during the equinox period. For 95% of the locations, an error of 2.42° ± 0.41° was found during non-equinox periods and up to 12.08 ± 3.63° during equinox periods. As expected the worst estimates were within equinox periods.

I surmised the number of days sampled (n = 28 in February and n = 7 in August) could have influenced the level of location accuracy since the estimation of location is calculated by iteration from previous daily estimates (Wildlife Computers 1994). When I compared the first 7 days of the two Razorback deployments there was no statistically significant differences in estimates of latitude and longitude (P = 0.29 and 0.34, respectively). However, remaining stationary for long periods produced estimates of greater accuracy with higher confidence levels than short or moving deployments. But marine mammals are only relatively stationary while at sea during foraging bouts and thus the benefits associated with making iterations from previous geolocations may well be reduced on free-ranging deployments while they are travelling. The estimates of location by GLTDR could be more accurate when the subject is remaining in an area for extended periods while foraging or hauled out for example.

3.4.3: At-Sea Deployments

Le Boeuf (2000) found differences between the location of a PTT glued to a free-ranging northern elephant seal and a concurrent geolocation could be as much as 5°. This was also the case for deployments in this study. When I compared the radial error between a PTT location and a concurrent geolocation from a migrating elephant seal I found the error was worst (±3.86°) between latitudes 55-60°S in non-equinox periods and 7.3° between 50-55°S during equinox periods (Table 3.6). Filtered geolocation estimates (McConnell *et al.* 1992a) were closer to that of the PTT in all cases, but filtered equinox estimates were still very poor.

Aside from the commonly regarded influences on latitude variation (season and latitude itself), the seal's migration behavior could explain some portion of the inaccuracies in geolocations at latitudes between 50 and 60°S. During an adult seal's migration there are phases of movement, two rapid periods separated by a slower period probably associated with foraging bouts (Le Boeuf *et al.* 2000, Slip *et al.* 2001) and this was the case for each of the seals tracked here (van den Hoff unpublished data). Rapid rates of travel in any direction are likely to either extend or diminish the day length by some period of time. An inaccuracy in the timing of dawn and dusk of as little as 4 minutes can produce a 1° error in longitude and a changeable error in latitude depending upon time of year (Wildlife Computers 1993). Archival tags attached to Wandering Albatross (*Diomedea exulans*)

displayed this very well. From a satellite tracking study Jouventin and Weimerskirsch (1990) showed Wandering Albatross travel 900 km/day in an easterly or westerly direction, a distance far in excess of that for elephant seals (100–220 km.day^{-1}, Slip *et al.* 2001). From GLTDRs attached to Wandering Albatross Tuck *et al.* (1999) gave a potential longitude error of approximately 7.5° or between 350 and 600 km, depending on the latitude. This error was almost entirely due to the rapid movement in an easterly or westerly direction. Thus, although of a smaller scale the errors in elephant seal location by light level could be complicated during periods of rapid movement during the inward and outward portions of any migration.

Several studies have determined the error associated with each uplink class given by the ARGOS satellite system (see Goulet *et al.* 1999). Ideally, comparisons are made from data transmitted to the satellite while the study species or transmitter is stationary at a site where that location has been determined very accurately by global positioning system (GPS). However, there is often uncertainty about the location of the transmitter because it has fallen from the study animal at a remote location (Goulet *et al.* 1999) and different studies have used PTTs of different power output. When the seal used in this study was observed hauled out on Macquarie Island, its location was known to within 1 km. While seal B284 was ashore on Macquarie Island, only 9% of the locations transmitted were of the lesser qualities, LQ A or B, with a radial error of 20.5 and 32.2 km, respectively. Conversely, the majority (87.5%) of at-sea locations from seal B284 were in LQs A and B. Because LQs worse than class 0 cannot be given an accuracy by service ARGOS (ARGOS 1998), any information obtained during deployment is useful to a particular study. There was no reference points at-sea with which to check the at-sea location errors, but these at-sea LQs can be assigned on-shore accuracies. Elephant seals do compromise the quality of locations through their propensity to dive continuously (Le Boeuf *et al.* 1994) and surface for as little as 2 minutes. This behavior reduces the possibility of obtaining a good quality location fix from the ARGOS platform and the recording of accurate dawn-dusk times for geolocation. Assigning on-shore errors to at-sea locations is useful for species that transmit a large proportion of poor quality fixes. While ashore at Macquarie Island the error in location of the PTT was approximately 0.25° or about 30 km at worst.

The deployments in this study provided insufficient data within the weekly and five-degree bins from the at-sea deployments to construct cumulative percentage plots of geolocation error from the PTT (Figure 3.11). However, the findings from these deployments indicate an error of ± 2° to ± 4° can be expected between a filtered geolocation and a daily PTT location, depending on latitude and week of the year (Table 3.6 and Figure 3.11). More deployments are needed to determine the cumulative percentage such as that described herein for the stationary platform and seal-based on-shore deployments. Their use will be in establishing the spatial scale at which locations can be plotted in correlation to satellite derived parameters such as sea-surface temperature (SST) and primary productivity (chlorophyll *a*), for example.

3.5 RECOMMENDATIONS

If a confidence level of 68% for geolocations is suitable to the researcher, then the scale for correlating sea surface temperature (SST), bathymetry, ocean colour (primary productivity) or ocean frontal zones with geolocation estimates for far ranging marine mammals such as elephant seals, is a grid box no smaller than 3° square. If a 95% confidence level is required then the box should be no smaller than 5°.

These figures should be used only during non-equinox periods. Outside these periods the error is far too large (up to ± 21°). For any sensible conclusions to be drawn, a latitude correction using longitude in combination with one or more of the parameters such as SST, dry period (haulout), ambient temperature and/or dive depth should be applied or the data rejected out of hand. The scale at which correlations can be made for satellite transmitted locations is also dependent upon the fix quality. For elephant seals making at-sea migrations from Macquarie Island the LQ for ARGOS data was in the order of ± 20 to 32 km or approximately 0.5° x 0.5°.

3.6 CONCLUSIONS

Tracking marine mammals that forage and migrate over long distances toward or within polar latitudes (elephant seals in this case) can be achieved using geolocation because the accuracy of location estimates increases with increased latitudes and their migration distances are far greater than the error associated with

that method. However, because of these relatively large errors the scale at which geolocations can be correlated with ocean features are mesoscale (100s of km) at best. For fine scale correlations satellite or GPS positioning is mandatory. Otariid species migrate shorter distances than most phocids (Table 3.7) and the distances are generally less than or equal to the error of the geolocation itself (± 220 km). Thus geolocation of some pinniped species is not a suitable method for ecological studies. Geolocation may have value in studying aspects of other species such as marine turtles, small cetaceans and some sea birds that migrate long distances (Table 3.7).

Geolocation time-depth recorders are a very useful tool for tracking most land breeding marine mammals to their foraging grounds in large numbers because the cost is small and the scale at which the results are used is most suitable for management related fisheries questions.

Table 3.7: Migration range for selected pinnipeds and marine turtles.

Species	Location	Migration range (km)	Source
Otariidae			
SubAntarctic fur seal			
Arctocephalus tropicalis	Amsterdam Is.	260±170	Georges *et al.* 2000
Antarctic fur seal			
A. gazella	Îles Kerguelen	68-575	Bonadonna *et al.* 2000
	South Georgia	350-900	Boyd *et al.* 1998
New Zealand fur seal			
A. fosteri	Otago, N.Z.	<50-220	Harcourt and Davis 1997
Hookers sea lion			
Phocarctos hookeri	New Zealand	*ca.*1 000	van den Hoff pers. obs.
Steller sea lion			
Eumetopias jubatus	Latax Rocks	20-300	Merrick *et al.* 1994
Phocidae			
Northern elephant seal			
Mirounga angustirostris	California	540-4 259	Le Boeuf 2000
Southern elephant seal			
M. leonina	Marion Island		Jonker and Bester 1998
	Macquarie Island	2 000	Slip, *et al.* 1994
	Heard Island	2 500	Slip, *et al.* 2001
	South Georgia	3 000	McConnell and Fedak 1996
	Patagonia	. 2 300	Campagna *et al.* 1998
Ringed seal			
Phoca hispida	West Arctic	220-2 000	Gjertz *et al* 2000a
Spotted seal			
P. largha	Chukchi Sea	28-1 680	Lowry *et al.* 1998
Harbor seal			
P. vitulina	California Bight	48	Stewart *et al.* 1989
Crabeater seal			
Lobodon carcinophagus	Antarctic Pen.	500	Bengtson *et al.* 1993
	Weddell Sea	720-1 900	Bornemann and Plötz 1999
Bearded seal			
Erignathus barbatus	Norway	180 -960	Gjertz *et al.* 2000b
Grey seal			
Halichoerus grypus	Donna Nook	10-265	McConnell *et al.* 1992b
Weddell seal			
Leptonychotes weddellii	Antarctic Pen.	150	Bengtson *et al.* 1993
Turtles			
Olive Ridley turtle			
Lepidochelys olivacea	Costa Rica	1 400-2 300	Plotkin *et al.* 1995
Green turtle			
Chelonia mydas	South China Sea	600	Papi *et al.* 1995
Loggerhead turtle			
Caretta caretta	Natal	500-1 000	Papi *et al.* 1997

CHAPTER 4

MIGRATIONS AND FORAGING AREAS OF JUVENILE SOUTHERN ELEPHANT SEALS (*Mirounga leonina* L.) FROM MACQUARIE ISLAND: ESTABLISHED BY GEOLOCATION

4.1 INTRODUCTION

The southern elephant seal (*Mirounga leonina*) population at Macquarie Island declined by approximately 50% from 1949 to 1985 (Hindell and Burton 1987) and has continued declining at approximately 1.2% per annum since 1985 (Australian Antarctic Division, unpublished data). There are several hypotheses put forward that suggest causes for the Macquarie Island decline but high first year mortality (increased pup mortality at sea), perhaps owing to reduction or shifts in prey availability, is thought to be the ultimate cause for the decline (e.g., Hindell and Burton 1987, Hindell *et al.* 1994a). First year survival is significantly correlated with the pup's mass at weaning (McMahon *et al.* 2000c). The survival of pups in their first year was, recently, much higher ~ 65% (McMahon *et al.* 1999) than during the 1960s (2–48%, Hindell 1991).

As the decline continues, other hypotheses that may contribute to first year mortality have also been investigated. The influence of human and research disturbance on mother-pup behavior during the critical suckling period and resultant wean weight (ie maternal investment) was investigated and found unlikely to cause lower survival of handled or disturbed pups and adults (Wilkinson and Bester 1988, Engelhard *et al.* 2001, Engelhard *et al* in review). Burton and van den Hoff (in press) have shown that there is currently little effect of pollutants on populations of southern elephant seals, and that fisheries overlap with the known prey of the seals is minimal in species terms (also see Goldsworthy *et al.* 2001) and in prey size (John van den Hoff, unpublished data). However, commercially harvested species do form a large component of the biomass consumed by the seals (e.g., the Ommastrephid squid *Martialia hyadesi*). Much of the knowledge gathered so far regarding southern elephant seal diet is restricted by sample collections taking place at their breeding locations. Very little is known of the diet of southern elephant seals when they are distant from the breeding locations.

Increased interest in commercial fisheries in the Southern Ocean may further complicate the status of southern elephant seal populations if the removal of prey and the increased probability of gear interactions do occur. However, this will depend on the commercial target species and location of the fishery relative to the foraging grounds of the seals. Thus, an understanding of the foraging migrations, diet and feeding ecology of young (and older) seals is important for establishing what factor(s) may influence survival of pups and juveniles and, consequently, demography of southern elephant seals.

Elephant seals are long-lived mammals, up to 23 years (Hindell and Little 1988) and foraging is an important phase in their annual cycle. The seals must obtain sufficient energy reserves (stored as blubber) to live through periods of fast such as the annual moult and breeding season. The breeding season has different demands for both sexes. Adult males of beach-master and challenger status fast for four months as they fight for harem control and breeding success, while females invest resources in a single pup each year for many years after reaching breeding age between three - six years. For seals of all ages to be successful they must locate prey with some assurance for many years. Much of the information about foraging by southern elephant seals has been gathered for adult seals (for details see Hindell *et al.* 1991a, Bester and Pansegrouw 1992, McConnell *et al.* 1992a, McConnell and Fedak 1996, Slip *et al.* 1994, Slip 1997a, Jonker and Bester 1998, Campagna *et al.* 1999, Slip *et al.* 2001).

Little is known of foraging locations by juvenile southern elephant seals (Slip 1997b, Bornemann *et al.* 2000) though some research has recently been done with juvenile northern elephant seals (Le Boeuf *et al.* 2000). In 1962, Carrick and Ingham thought yearling southern elephant seals from Macquarie Island did not move far from their birth sites, perhaps only to the narrow limits of the shelf area surrounding the island. However, juvenile seals marked on Macquarie Island have been observed to migrate to islands on the Campbell Plateau south of New Zealand, and to Tasmania (Nicholls 1970, van den Hoff 2001a). One hot-iron branded yearling has migrated from Macquarie Island to Peter 1 Øy (Hindell and McMahon 2000), a return distance of approximately 10 000 km. Completed migrations over 900 km for juvenile seals born at Marion Island and Heard Island (Bester 1989, Slip 1997b), and incomplete migrations of 2 000 km for juvenile seals from King George

Island (Bornemann *et al.* 2000) are also documented. Thus, young elephant seals are not sedentary during their first years of life as suggested by Carrick and Ingham (1962), and there may be important age-related similarities and differences in foraging that impact upon the general population vitality and ecology.

Concentrations in the distribution and abundance of breeding and foraging seabirds is usually taken to reflect the availability of prey in the marine ecosystem upon which they depend (Hunt 1991). Ecological factors influencing the at-sea distribution of marine predators can be observed at multiple levels from fine scale (10 s of m to 100 km) to meso and coarse scales (100s of km to > 100 km) (Hunt 1991). Fine to coarse scale studies of adult elephant seal foraging have shown the foraging ground distribution for some seals appears correlated with water masses of specific temperatures and frontal systems (Hindell *et al.* 1991a, McConnell *et al.* 1992, Field *et al.* 2001) and some with bathymetry (McConnell *et al.* 1992a, Jonker and Bester 1998, Campagna *et al.* 1999).

My objectives in this chapter were to:

1) document migration routes and the direction of foraging grounds for juvenile elephant seals during their second and third foraging trips (i.e when aged 6-10 months and 12-14 months).
2) determine if the study seal's survivorship was compromised by the attachment of tracking instruments.
3) determine at a meso scale (100s of km) if oceanic areas with specific water temperatures or bathymetric features are foci for foraging by the seals.
4) establish if the foraging grounds for juveniles overlap with adult seals.
5) determine if the seals are foraging within areas where current commercial fisheries are located.
6) compare the known diet of elephant seals from Macquarie Island with the target species of the nearby commercial fisheries.

4.2 METHODS

4.2.1: Study Animals and Field Procedures

The study used juvenile southern elephant seals (6 – 14 months old) hauled out on the isthmus at Macquarie Island (158° 57'E, 54° 30'S, Figure 3.1). The age of some seals was known either from tags (Jumbo tags, Dalton Supplies Woolgoolga, NSW) placed in the hind flippers at birth or from hot-iron brands applied at weaning (McMahon *et al.* 1994). If age was unknown, an estimate was made from length/age group classifications (Antarctic Division unpublished data, Rodhouse *et al.* 1992). All seals with the brand letter prefix "A" are seals of estimated age the remainder are known age. Age classes 6 - 10 months and 14 - 15 months corresponded to second and third foraging trips, respectively.

Seals were captured with a canvas head bag and the administration of an intravenous injection of ketamine (2.0-3.0 mg/kg) and diazepam (0.05-0.2 mg/kg) (Slip and Woods 1996) or Zoletil 100 (Virbac, Australia, McMahon *et al.* 2000a) anaesthetised the seals while the seal was weighed and the instruments attached.

To determine at-sea position, an archival microprocessor-controlled geolocation time-depth recorder (GLTDR) and a VHF transmitter (Advanced Telemetry Systems, Minnesota, USA) were attached with epoxy glue (Araldite K268, Ciba-Geigy) to the dorsal mid-line, approximately 60 cm from the tip of the nose of 43 juvenile southern elephant seals. The GLTDRs were programmed to record light-level readings and sea-surface temperature to a maximum depth of 20 meters, for 2 minutes at a minimum interval of 20 minutes.

Daily searches of the isthmus and regular whole island searches were made for instrumented seals. Upon return to Macquarie Island the seals were re-captured, anaesthetised, re-weighed, their stomachs lavaged (Slip 1995), and the tracking instruments removed.

4.2.2: Data Analysis, Geolocation Error and Improving Location Estimates within Equinox Periods

Most seals remained ashore for a number of days after being instrumented. Thus, to determine the at-sea mass change for migrating seals the departure mass was corrected by subtracting 1.9 kg for each day the seal remained ashore after

weighing and prior to departure (Australian Antarctic Division, unpublished data). The foraging trip mass change was calculated as the difference between the corrected departure mass and the mass measured upon return to the island.

Migrations and foraging areas were established from the TDRs geolocation option that gathered light-level intensity and sea-surface temperature. Wildlife Computers GEOLOCATION analysis software version 2 was used to estimate geographic location from the stored hexadecimal files. I used only the dawn/dusk (DD) times to calculate position because Wildlife Computers has established these times can more accurately locate than sunrise/sunset (RS) times using light-level readings (Wildlife Computers 1993). From light-level readings one location range, given as decimal degrees latitude and longitude, was estimated per 24-hour period. An error of ± 3° of latitude and longitude was attributed to each daily location (van den Hoff *et al.* in review a, Chapter 3).

Equinox period latitude estimates were improved from the following assumptions:

1) that there was no difference in each GLTDRs ability to determine longitude (van den Hoff *et al.* in review a, Chapter 3).

2) that longitude was accurate to within ± 1° (DeLong *et al.* 1992).

3) that latitude estimates could be improved with reference to the GLTDRs stored dawn sea-surface temperatures (SST) and multi-channel sea-surface temperature (MCSST) data provided by the PO.DAAC AVHRR NASA server.

I used the GLTDRs dawn SST because the influence of solar radiation at the surface is likely to be at a minimum at that time. The influence of the seal's body temperature upon the thermistor is also thought to be minimal (McCafferty *et al.* 1999). After correlating the longitude estimate and sampled SST with the MCSST data, I replaced equinox latitudes with the MCSST derived latitudes and then filtered poor quality locations from the output files by using a velocity maxima of 3 $m.sec^{-1}$ (12.5 $km.hr^{-1}$, after McConnell *et al.* 1992a). I then plotted the corrected positions within 3° grid squares (± 1.5° error) because Hill (1994) suggested that each geolocation should be presented as a rectangle with a given level of confidence. Any position within the range has an equal likelihood of being the best estimate and the mid-point of the range is not necessarily "the most probable location" (Wildlife

Computers 1993). Sixty-eight percent of the location estimates are likely to fall within this sized grid (van den Hoff et al in review, Chapter 3).

4.2.3: Spatial Analyses

Migration range was calculated as the great circle distance measured (in km); from Macquarie Island to the most distant location recorded for each individual. Migration duration was determined either directly from the GLTDR data or from observed departure and return dates of the seals. Positions of ocean frontal features are plotted after Orsi *et al.* (1995).

The proportion of time that seals spent in relation to ecologically related ocean features and fishery boundaries was calculated from each seal's foraging trip using 3° by 3° grids referenced to latitude 0° and longitude 0°. Each filtered location was assigned to a 3° x 3° grid each of which was identifiable by a nodal latitude and longitude. Each seal's entry and exit times for the squares were taken from the GLTDR file. The time spent in each square was summed for each individual seal, each age class and each sex unless otherwise specified. The percentage of the total time was then calculated from the data. Age and sex were treated separately for ecological aspects and pooled for fishery overlap.

Survivorship estimates were calculated from resight records (ie. the encounter history) for each seal fitted with a TDR. The resulting matrix was analysed using Program MARK (White and Burnham 1999) and compared with first year survival of non-instrumented seals. I did not test specifically if the input data violated the assumptions within a Cormack-Jolly-Seber (CJS) model because heterogeneity in the survival and/or recapture probabilities, and departures from the CJS model assumptions do not affect point estimates of survival (Carothers 1979) although they do cause underestimation of the standard errors for each survival estimate (Burnham *et al.* 1987). In this case there were no significant differences between the groups and a any increase in size of the standard error would make no difference to the result overall.

4.2.4: Statistical Analyses

Preferential dispersal direction of seals from Macquarie Island was analysed using circular distribution statistics (Zar 1984). I grouped the angles into 9°

increments, producing 36 bins within which the abundance of seals was established. For Chi-squared analysis, frequencies within angle groupings were pooled until no expected frequency was less than 4 (Zar 1984).

Survival estimates for age classes and sex were compared using Chi-squared. I used a two-sample *t*-test analysis, with pooled variances, to test mass changes during foraging. A value with $P \leq 0.05$ denoted a significant difference through out.

4.3 RESULTS

4.3.1: Recoveries and General Findings

Thirty-two of the 43 GLTDRs deployed were recovered, 22 of these contained data (Table 4.1). Eight seals (19%) were never seen again, two seals returned but were missed during island surveys, their resights being made in subsequent years but the units never found. One seal (B141) returned with only a very small amount of data and is used only in certain analysis. Five GLTDRs had sufficient memory to track the seals for their entire migrations, 6 recorders tracked seals to a point on their return journeys and 12 ceased to record while the seals were either outward bound (1) or at foraging areas (11).

Nine of the 43 seals weighed prior to their departure were re-weighed upon return to the island, (Table 4.2). A two-sample *t*-test, with pooled variances, found no differences between departure mass of trip two and trip three seals. Seals aged 10 months weighed on average the same as 14-month-old seals at departure (Table 4.2, 113.7 ± 7.6 vs. 114.5 ± 5.2, $t_{(7)} = -0.08$, $P = 0.94$). Older seals (14 months) gained significantly more mass at a faster rate than younger seals ($t_{(7)} = -3.24$, $P = 0.014$ and $t_{(7)} = -2.45$, $P = 0.044$, respectively). Seals returning from foraging trip two gained 0.36 ± 0.03 kg.day^{-1} while seals returning from trip three gained 1.00 ± 0.18 kg.day^{-1} (Table 4.2).

Table 4.1: Deployment season, sex, age, days at sea, distance ranged, direction travelled to foraging ground, SST recorded during the fifth week of migration and the main foraging area for juvenile southern elephant seals tracked from Macquarie Island during 1993 and 1995. N.D. = Not Determined, * outward track only, CP = Campbell Plateau, APF = Antarctic Polar Front, MIZ = Marginal Ice-edge Zone, OO = Open Ocean, SACC = Southern boundary of the Antarctic Circumpolar Current, WHO = Winter Haul Out, PM = Post-moult,

Season	Seal	Sex	Age (months)	Days at Sea	Range from M.I. (km)	Bearing (degrees)	SST (Week 5)	Foraging ground/s
WHO	A20	F	10 - 11	98	1864	46	8.58 ± 0.91	CP
WHO	A33	F	10 - 11	110	893	255	1.98 ± 0.17	APF/OO
WHO	A34	F	10 - 11	176	1085	252	1.63 ± 0.17	APF/OO
WHO	A35	F	10 - 11	171	3319	96	2.90 ± 0.32	MIZ/OO
WHO	A37	F	10 - 11	89	811	200	0.79 ± 0.25	SACC/OO
WHO	A46	F	10 - 11	106	2587	95	5.25 ± 0.70	APF/OO
WHO	A57	F	10 - 11	88	1036	248	1.61 ± 0.12	APF/OO
WHO	F898	F	9	175	2259	139	1.76 ± 1.03	SACC/MIZ
WHO	H355	F	8	183	908*	150	N.D.	APF?
WHO	A31	M	10 - 11	80	818	66	8.80 ± 0.16	CP
WHO	A36	M	10 - 11	90	926	279	0.88 ± 0.29	OO
WHO	A38	M	10 - 11	116	1248	93	6.74 ± 0.75	CP
WHO	A51	M	10 - 11	86	1666	77	8.38 ± 0.06	CP
WHO	A76	M	10 - 11	121	2013	99	2.59 ± 0.17	APF/OO
WHO	F230	M	9	164	2390	119	0.84 ± 0.35	APF
WHO	F995	M	8	174	**3258**	102	4.71 ± 1.11	APF/OO
PM	A188	F	12 - 14	121	1457	259	2.95 ± 0.59	APF
PM	A189	F	12 - 14	67	**769**	239	2.96 ± 0.05	APF
PM	A180	M	12 - 14	105	1556	253	2.97 ± 0.27	APF
PM	A193	M	12 - 14	72	**826**	125	3.91 ± 0.11	APF
PM	A195	M	12 - 14	89	**1445**	120	3.91 ± 0.12	APF
PM	A196	M	12 - 14	80	**1380**	92	2.08 ± 0.31	CP/OO

Table 4.2. Mass at departure, gain while at sea and rates of mass gain while at sea for juvenile seals fitted with geolocation time-depth recorders on Macquarie Island. * = corrected mass

Foraging trip	Seal	Sex	Age (mths)	Departure mass (kg)*	At-sea mass gain (kg)	Rate of mass gain (kg/d)
Two	A20	F	10	98.5	38.5	0.39
	A51	M	10	121.8	34.2	0.40
	A76	M	10	120.9	36.1	0.30
Mean ± SE				**113.7 ± 7.6**	**36.3 ± 1.2**	**0.36 ± 0.03**
Three	A188	F	14	103.0	62.0	0.51
	A191	F	14	104.1	82.9	0.93
	A193	M	14	136.6	107.4	1.49
	A194	M	14	119.8	98.2	0.68
	A195	M	14	115.5	140.5	1.58
	A196	M	14	107.7	66.3	0.83
Mean ± SE				**114.5 ± 5.2**	**92.9 ± 11.9**	**1.00 ± 0.18**

There was a directed manner ($\chi^2 = 14.3$, $df = 5$, $P<0.05$) in the dispersal of seals to foraging areas distant from Macquarie Island. Significantly more seals travelled south than north ($\chi^2 = 61.1$, $df = 1$, $P<<0.001$) and the direction of travel used by 43% of the seals was a bearing south-east of Macquarie Island between 90-180°. A further 39% of seals travelled south-west between 180 –270° and the mean bearing of dispersion was 143.5° toward the ice-edge adjacent the Ross Sea (Figure 4. 1).

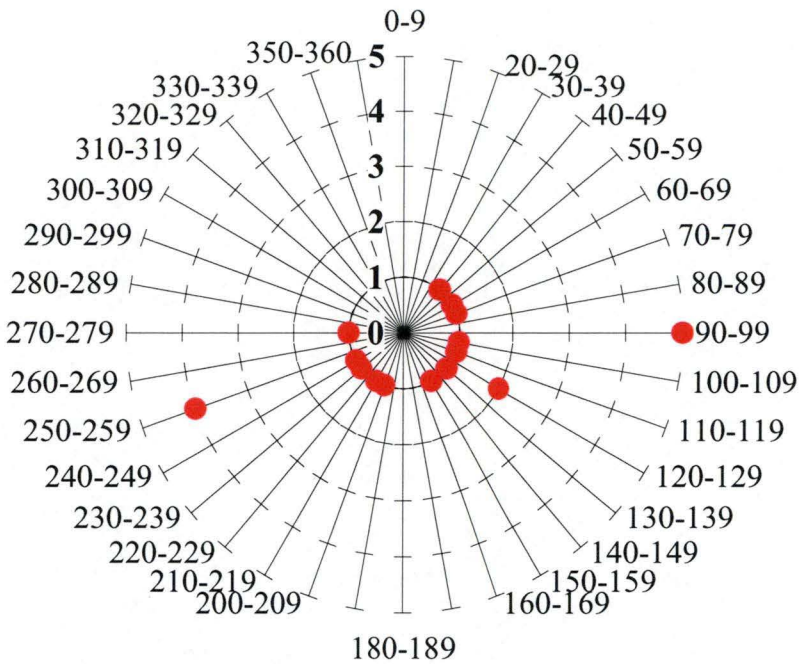

Figure 4.1: Non-random circular distribution of the foraging ground direction taken by juvenile southern elephant seals (n = 23) from Macquarie Island (χ^2 = 66.5, *df* = 22, *P*<<0.001). The mean direction of dispersal was 143.5°. X-axis represents the number of individuals recorded within each angle group.

4.3.2: Sea Surface Temperatures

The recorders recorded 1 675 dawn sea-surface temperatures (SSTs). From these records I excluded 240 temperatures recorded during the first five days of all migrations and last 5 days of return migrations so that foraging ground SSTs dominated the sample. The exclusion of these temperatures ensured I could identify if the seals tended toward a preferred ocean area that could be established from the SSTs. Seventy-five percent of SSTs recorded were ≤ 6° C (Figure 4.2), and 59% were between 1.0° and 4.0° C. Seventeen point eight percent of the temperatures were between 8° and 10° C.

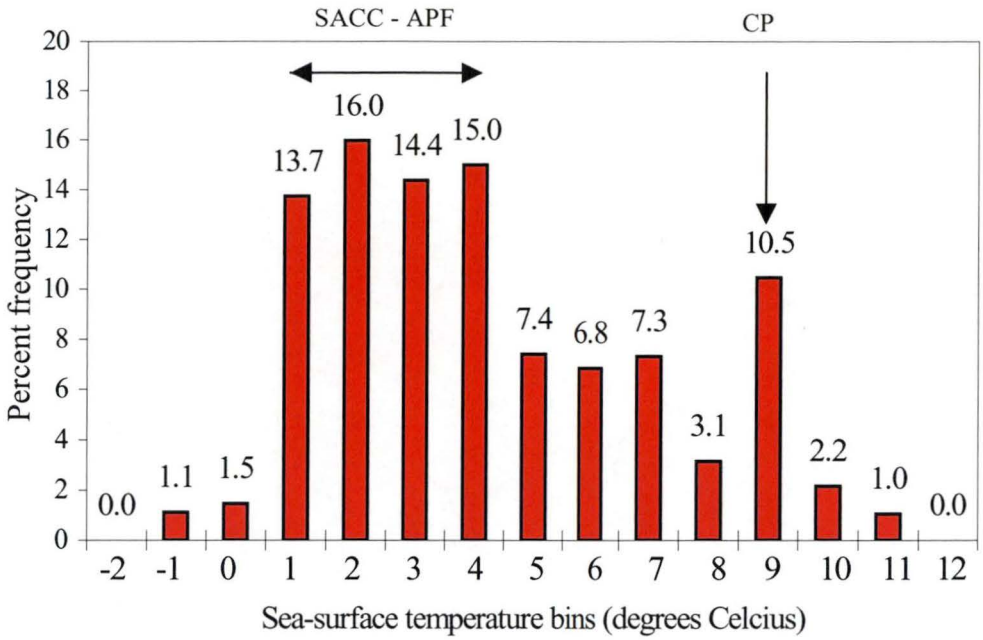

Figure 4.2: Percent frequency (figure at bar top) of sea-surface temperatures recorded by GLTDRs attached to juvenile elephant seals from Macquarie Island during 1993 and 1995. Note bin 0 = 0 – 0.9° C etc. n = 1 435. CP = Campbell Plateau. Other abbreviations as for Figure 4.4.

Individual seal records of SST during the foraging migration show some trends in the temperature profiles (Figure 4.3 A-F). In general, after an initial period of increase or decrease in SST as the seals move away from Macquarie Island, records show lengthy periods where the SST remains steady (e.g., A31 and A51, Figure 4.3B) or rapid increases and decreases in SST particularly at temperatures around 4° C (e.g., F995, Figure 4.3D).

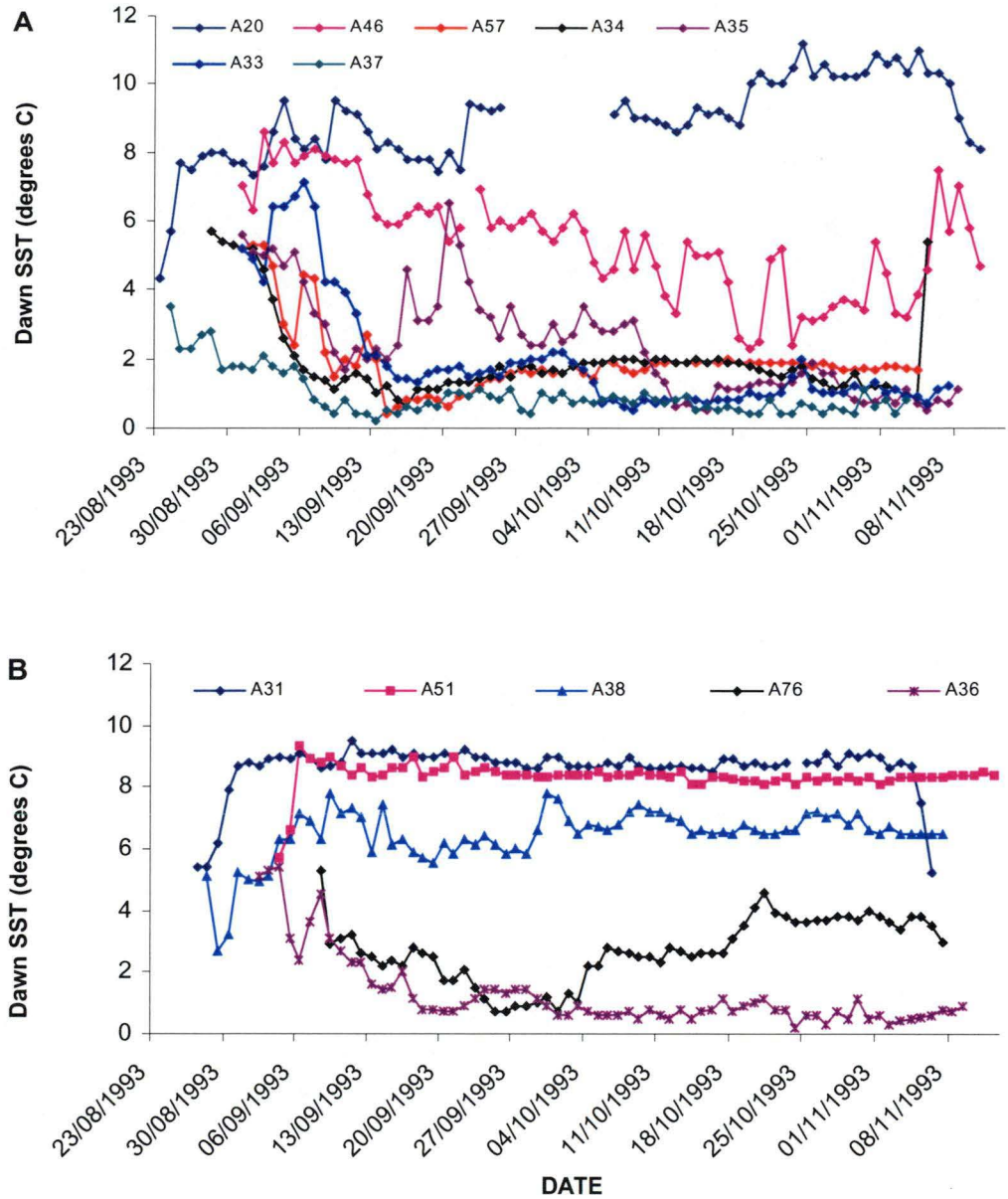

Figure 4.3: Sea-surface temperatures recorded during the foraging migrations of juvenile elephant seals from Macquarie Island during 1993 and 1995. A = 1993 mid-year haulout subyearling females. B = 1993 mid-year haulout subyearling males.

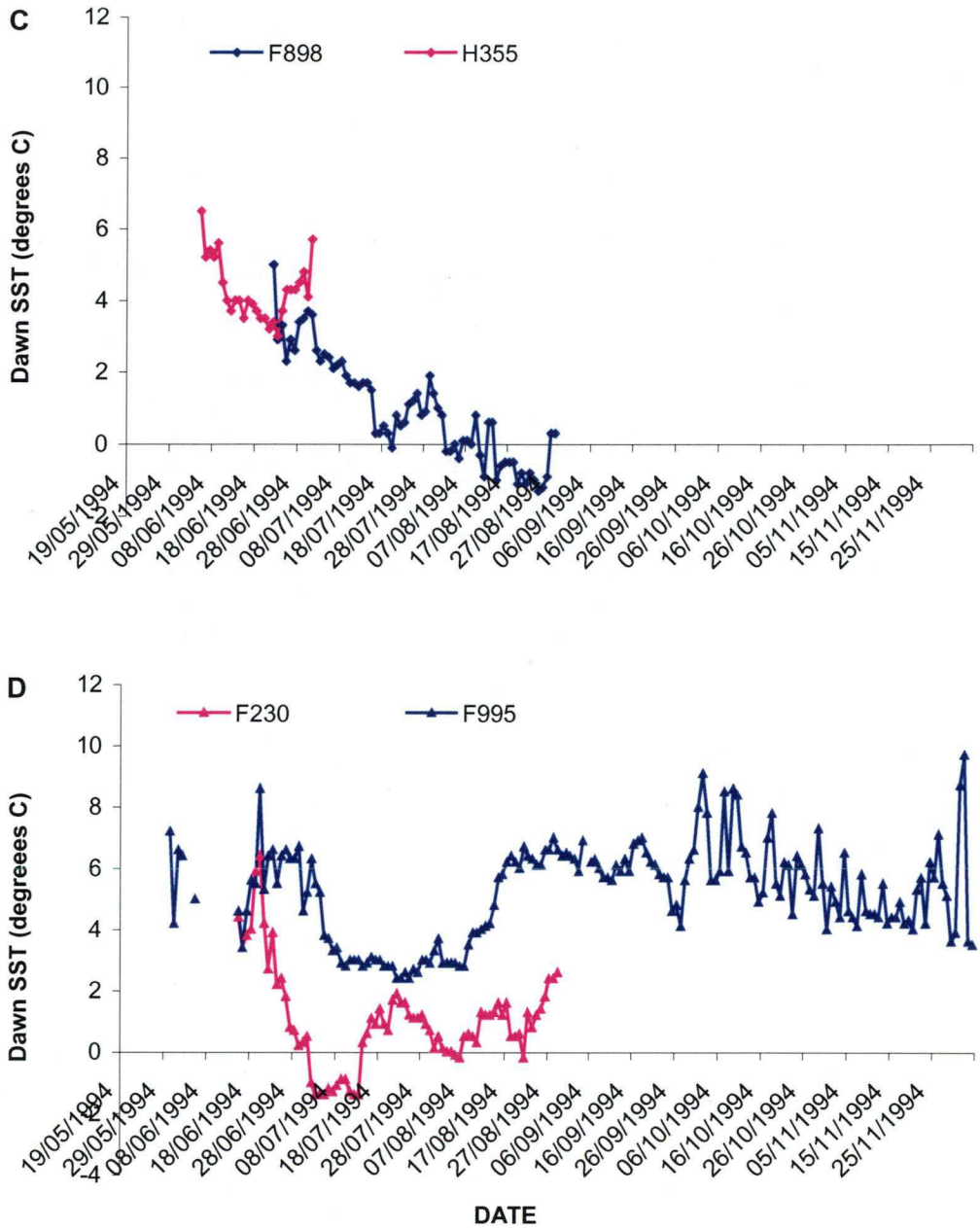

Figure 4.3 cont.: C = 1995 mid-year haulout subyearling females. D = 1995 mid-year haulout subyearling males.

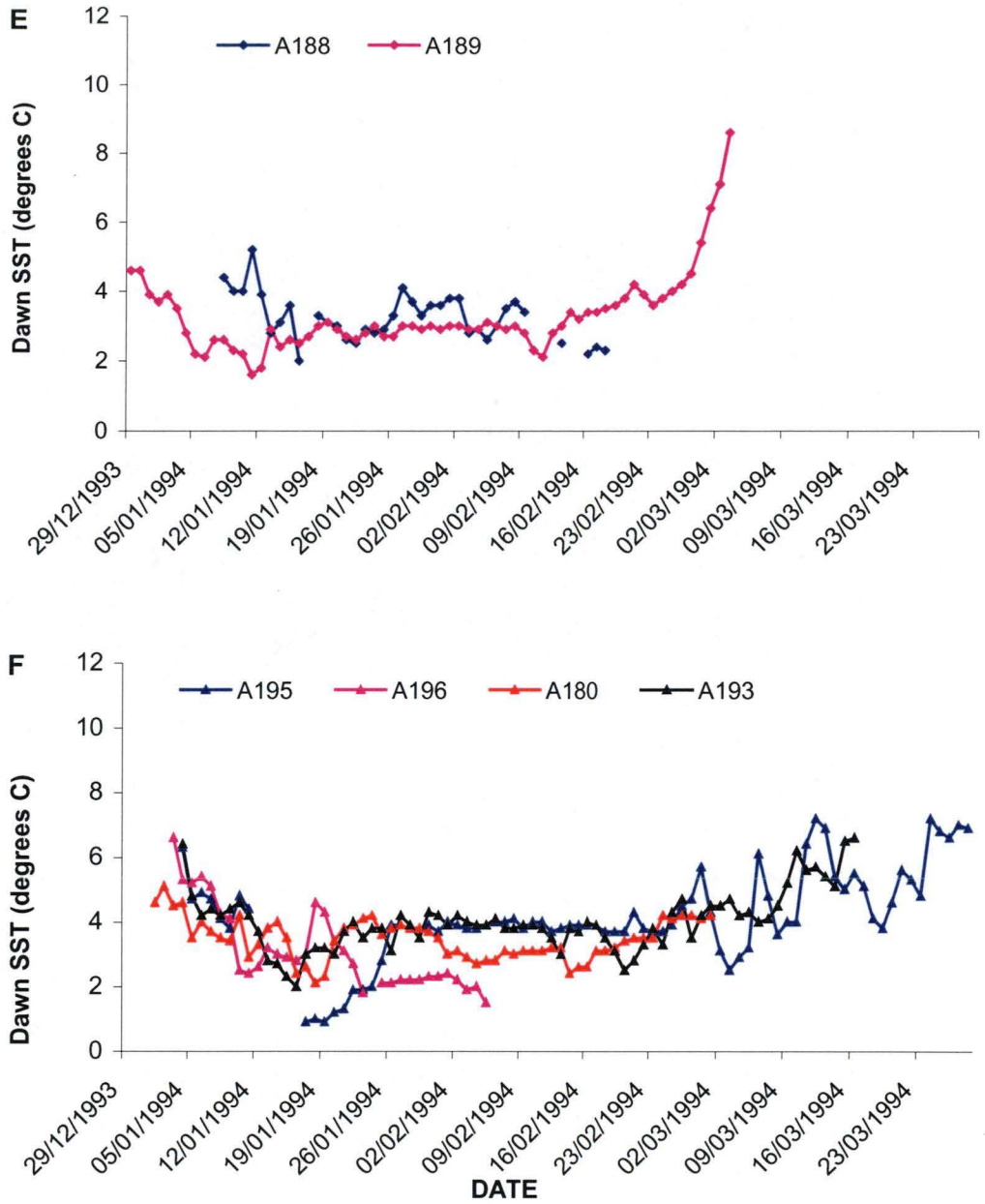

Figure 4.3 cont.: E = 1993 post-moult yearling females. F = 1993 post-moult yearling males.

4.3.3: Winter Haulout Underyearling Males (Figure 4.4)

Of the 7 male seals instrumented in August 1993, two (A31 and A51) moved north-east and remained over the Campbell Plateau for the duration of the deployment. Seal A31 was located in waters ranging from 500 – 2 000+ m deep where the SST was approximately 8.8°C. Seal A51 was located in waters < 1 000 m deep where the SST was near 8.4°C (Figure 4.3B). After initially migrating south, seal A38 travelled toward the Campbell Plateau and was located in waters approximately 2 000 m deep where the SST was near 7°C, (Table 4.1 and Figure 4.3B).

Seal A76 migrated south-east toward the Ross Sea, after which he moved to an area of open ocean to the north of the APF near 60°S and 170°W. The remaining seal (A36) travelled south-west in the open ocean near 60° S and 150°E. Both seals were located in waters exceeding 4 000 m depth. Sea-surface temperatures collected by A36 remained near 1°C for much of his migration while the record for A76 increased from a low of 1° to near 4°C after travelling north (Table 4.1 and Figure 4.3B).

Following their mid-year haulout in July 1995, two underyearling males (F230 and F995) migrated south-east to waters where the depth exceeded 4 000 m (Figure 4.4). Cold (-1 to +2° C) SSTs were recorded by these seals (Figure 4.3D) as they travelled south. The GLTDR fitted to seal F995 had sufficient memory to record the entire migration. The seal returned to Macquarie Island along a track to the north of his outward track in waters exceeding 4 000 m depth where SSTs fluctuated between 4 and 7° C.

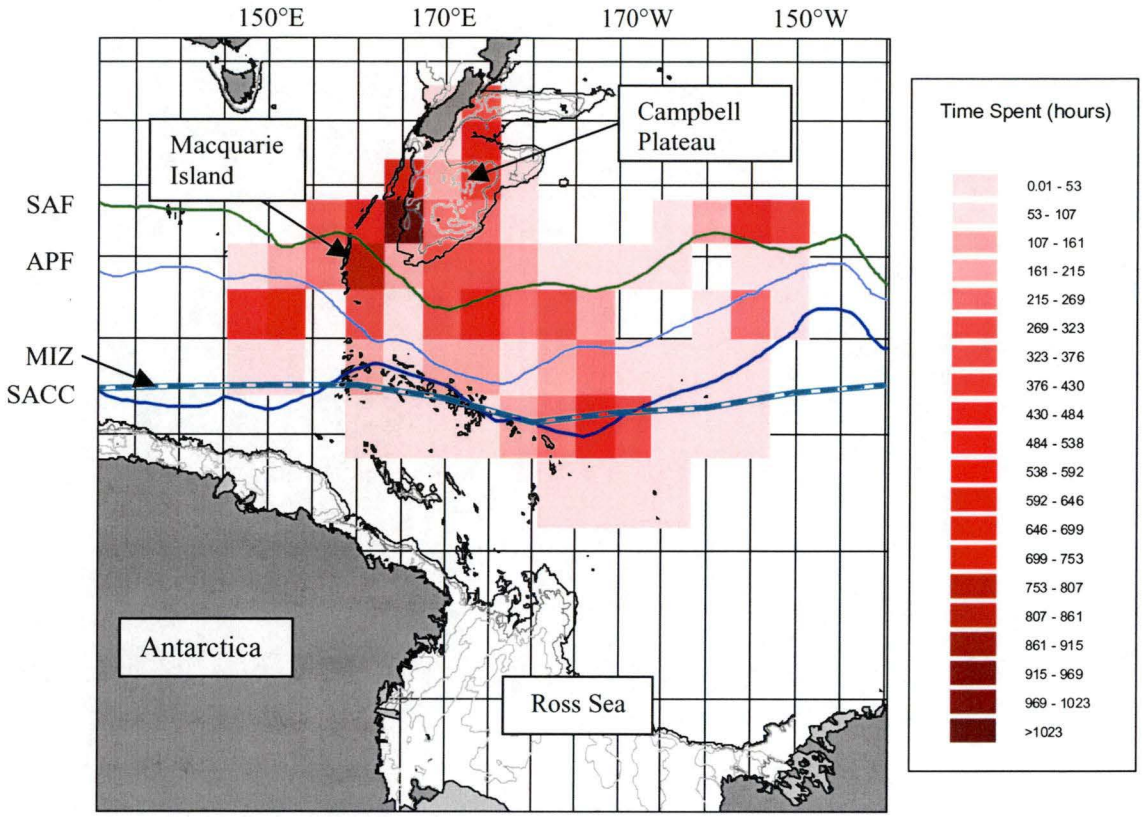

Figure 4.4: Time spent at sea within 3° grid squares by winter haulout underyearling male elephant seals from Macquarie Island. Darker shading = greater proportion of time spent. The grids are superimposed upon the regional bathymetry (dark line = 2000m, lighter lines are shallower in 500m intervals). The locations of oceanographic fronts in the study area are drawn from Orsi *et al.* (1995). SAF = Sub-Antarctic Front, APF = Antarctic Polar Front, SACC = Southern boundary of the Antarctic Circumpolar Current. MIZ = Marginal Ice-edge Zone (October)

Seals travelling to the Campbell Plateau ranged 1 244 ± 424 km, while seals A76 and A36 ranged 2 013 km and 926 km, respectively (Table 4.1). The migration ranges recorded for seals F230 and F995 were 2 390 km and 3 258 km distant from Macquarie Island, respectively (Table 4.1). Underyearling male seals spent on average 186.0 ± 5.6 days (n = 2) when departing in July and 97.4 ± 20.4 days (n = 5) at sea when they departed the island in August.

4.3.4: Winter Haulout Underyearling Females

Six of the seven female underyearling seals instrumented in August 1993 migrated to the south of Macquarie Island into the open ocean. The one female to migrate north, seal A20 reached latitudes near 45°S on the Campbell Plateau where SSTs were in excess of 10°C (Figure 4.3A), and the waters near 1 000 m deep.

Seals A35 and A46 migrated south-east, both seals then moved north to the open ocean where the depth was in excess of 4 000m and the SSTs recorded by A35 were about 3°C and 5°C for A46 (Figure 4.3A). Seals A33, A34 and A57 migrated south-west to an area where the water depth was >3 000 m and the SST was < 2°C for much of the time (Figure 4.3A). Female A37 migrated in a similar direction to the previous seals but remained further to the north where the SST was near 1°C.

Two female underyearlings, F898 and H355, instrumented in July 1995 migrated south (Figure 4.5). Seal F898 travelled into cold southern waters where the SST was near -1°C. She was the most southerly ranging female seal, reaching latitudes near 65°S. The short duration of tracking for H355 gave no indication as to the foraging grounds for this seal, however she was migrating east at the time the unit stopped recording.

Female underyearling seals spent on average 168 ± 7.8 days (n = 2) at sea if they departed in July and 107.4 ± 30.3 (n = 7) days at sea if they departed in August. The females ranged on average 1 731 ± 925 km (811 – 3 319 km) from Macquarie Island (Table 4.1).

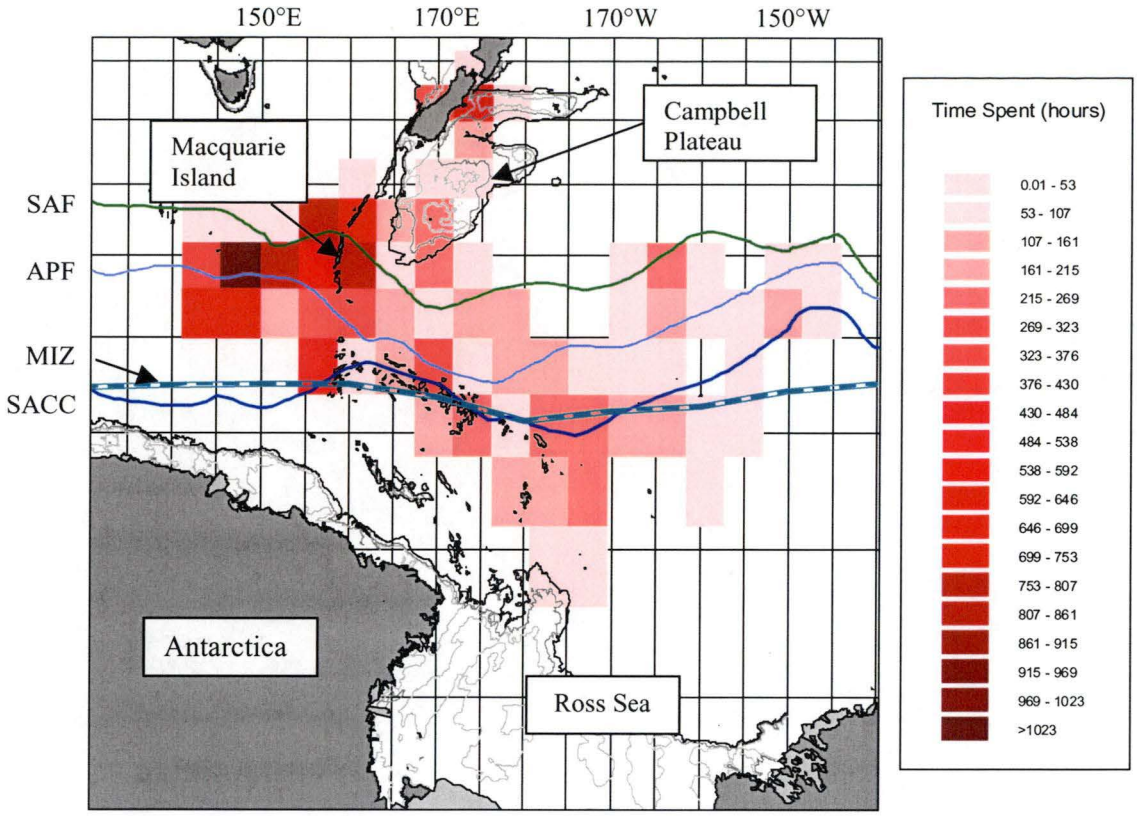

Figure 4.5: Time spent at sea within 3° grid squares by winter haulout underyearling female elephant seals from Macquarie Island. Features as for figure 4.4.

4.3.5: Post-Moult Yearling Males and Females (Figure 4.6 a, b)

Six seals aged approximately 14 months (4 male, 2 female) were tracked (Figures 4.6 a, b). One male A196, migrated east to waters ~5 000 m deep where the SST was near 2° C (Figure 4.3F). Male A195 migrated south-east into waters ~3 000 m deep where the SST was around 4° C. The remaining two male seals A180 and A193 migrated in opposite directions from the island into waters ~4 000 m deep where the SST was near 4° C. Both females (A188 and A189) migrated west into waters ~4 000 m deep where the SST was near 4° C (Figure 4.3E).

During foraging trip three, yearling seals spent on average 89.0 ± 20.6 days at sea. The females spent 94 ± 38 days at sea as they ranged on average 1 113 ± 486 km (n = 2,) from Macquarie Island (Table 4.1). Males travelled on average 1 300 ± 325 km (826 – 1556 km) in 87 ± 14 days (Table 4.1).

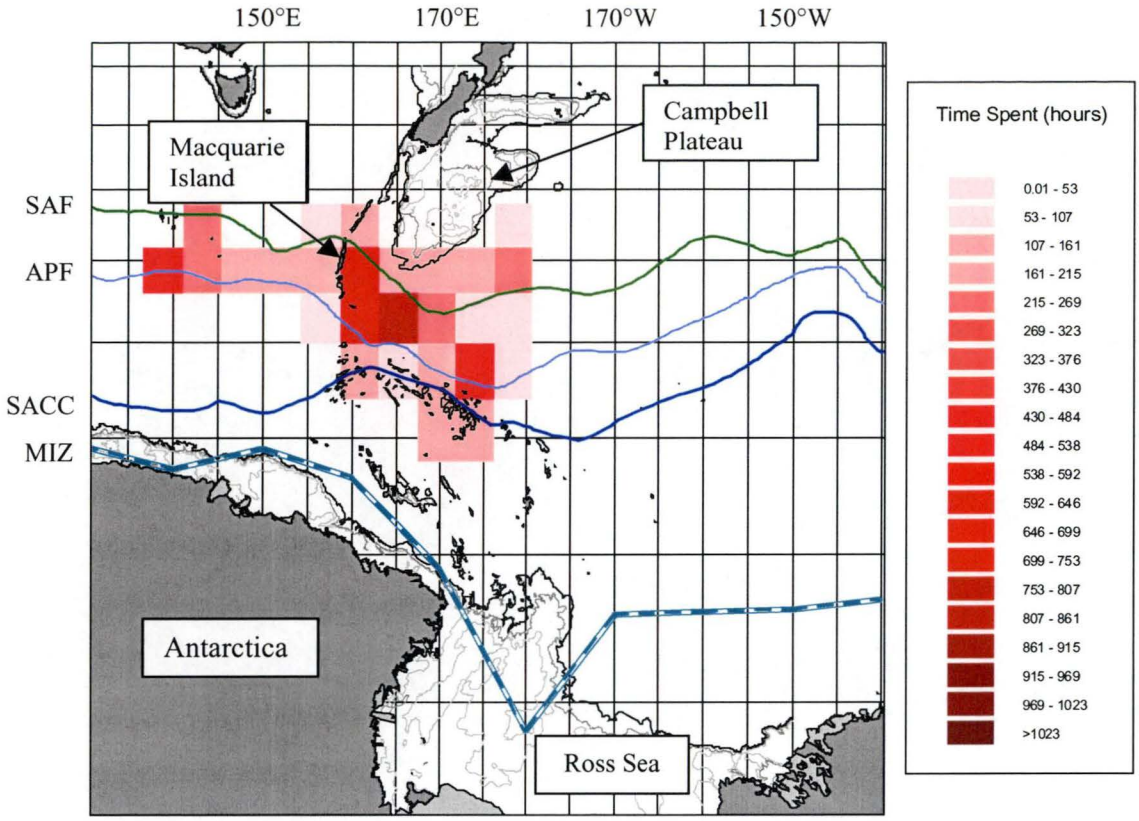

Figure 4.6 a Time spent at sea within 3° grid squares by post-moult yearling male elephant seals from Macquarie Island. MIZ = Marginal Ice-edge Zone (February). Other features as for figure 4.4.

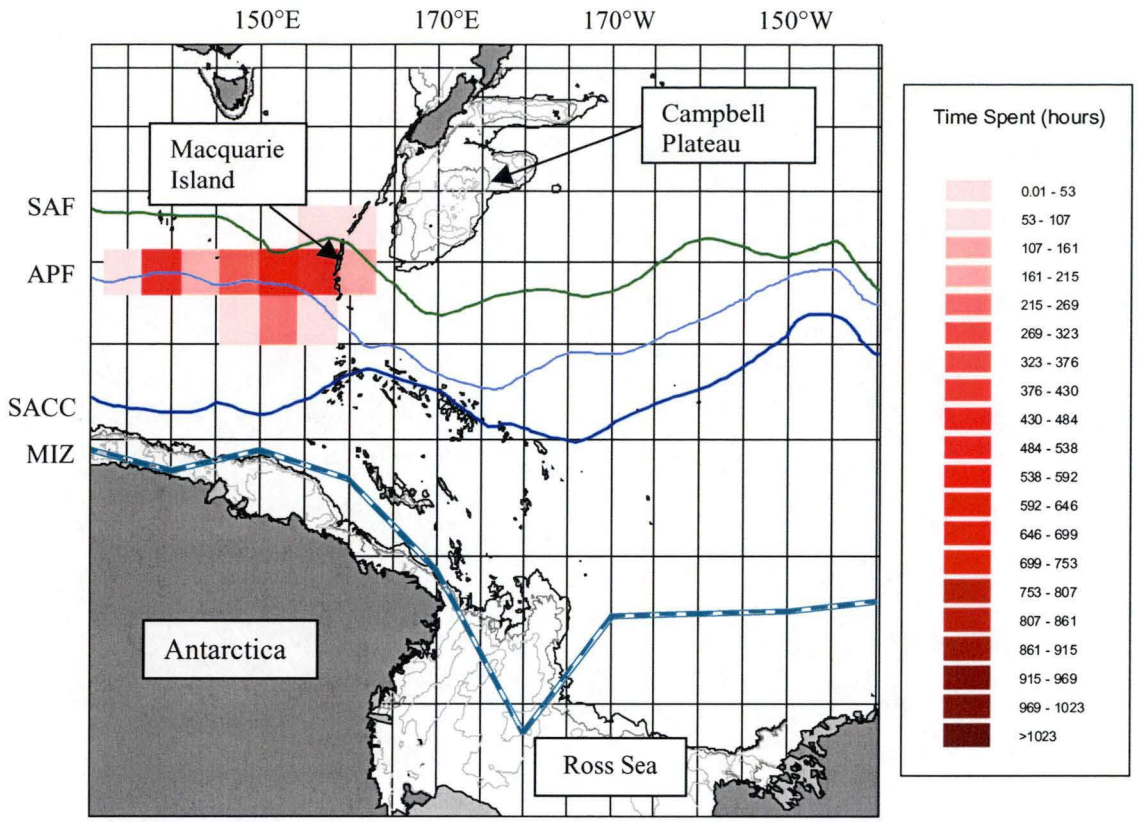

Figure 4.6 b Time spent at sea within 3° grid squares by post-moult yearling female elephant seals from Macquarie Island. MIZ = Marginal Ice-edge Zone (February). Other features as for figure 4.4.

4.3.6: Survivorship for Instrumented Seals

The survival estimates for the seals instrumented during this study are shown and compared with non-instrumented seals in Table 4.3. There were no differences in the survivorship between the sexes ($\chi^2 = 1.55$, $df = 3$, $P = 0.67$) or between age classes (underyearling vs yearling; $\chi^2 = 1.17$, $df = 3$, $P = 0.76$).

Table 4.3: Survival estimates (ϕ) (Mean ± SE) for seals carrying a GLTDR.

Foraging Trip	ϕ GLTDR Seals	95% confidence (lower)	95% confidence (upper)	ϕ Non-GLTDR Seals
Second	77.8 ± 5.4	65.4	86.7	74.3
Third	86.6 ± 9.3	57.2	96.9	86.7

4.3.7: Time Budgets: Ocean Features and Fishing Areas (Figure 4.7)

Juvenile seals spent most (72.2%) of their at-sea time in waters between the Antarctic polar front (APF) and north of the sub-Antarctic front (SAF) (Table 4.4, Figure 4.7). South of the SACC, near the MIZ was the least frequented zone. The relative importance of the zones is dependent on the age and sex of the seals; underyearling males spent more time north of the SAF, which incorporates the Campbell Plateau, than underyearling females.

A total of 38 228 hours of at-sea time was recorded for all the juvenile seals combined. Juvenile seals spent 58.6 % their time at-sea within administered fishing areas (Figure 4.7). They spent 14.9 % of time in the Macquarie Island Economic Exclusion Zone (MIEEZ), 17.7 % of time in the New Zealand Economic Exclusion Zone (NZEEZ), 14.1 % of time in CCAMLR statistical subsection 88.1, 4.0 % of time in CCAMLR statistical sub-section 88.2 and 9.4 % of time in CCAMLR statistical subsection 54.4.1. The total for CCAMLR is 27.5 %. The remaining 41.4 % of the time was spent on the high seas.

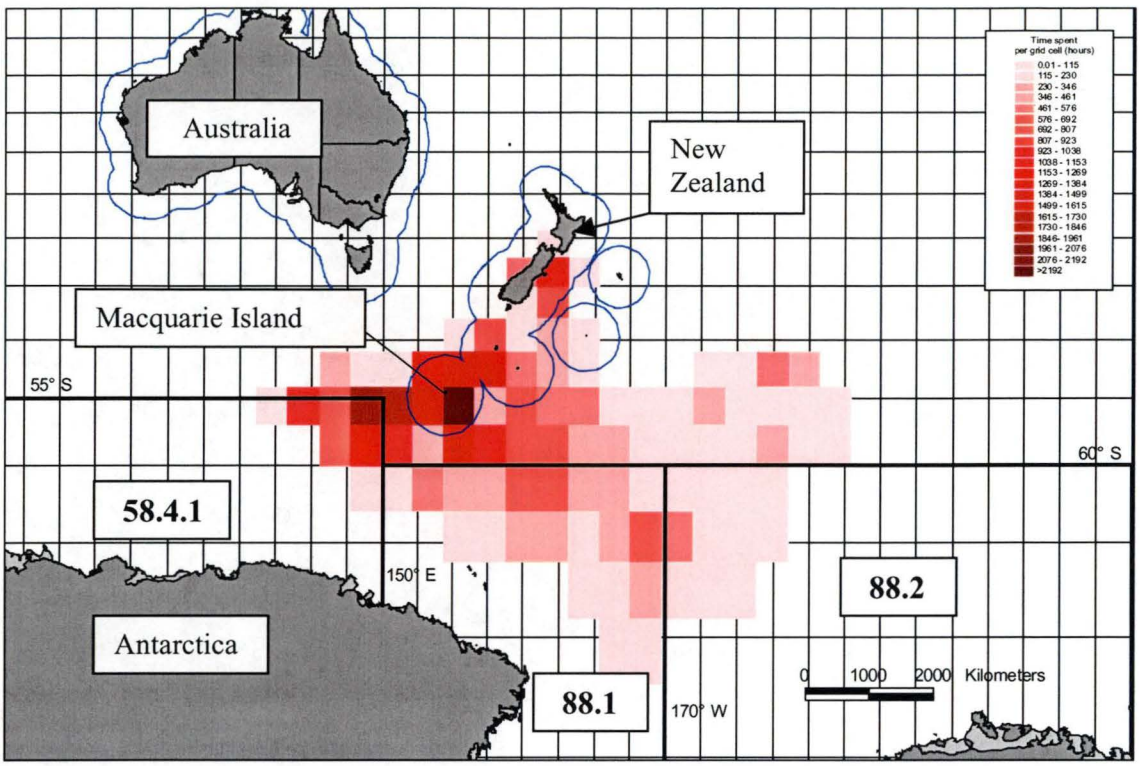

Figure 4.7 Time spent in 3° grid for all juvenile elephant seals during the study period; 200nm fishing zone limits (areas enclosed by blue lines) and CCAMLR sub-section area boundaries 58.4.1, 88.1 and 88.2 within the Southern Ocean study area are shown. nm = nautical mile.

Table 4.4: Number of hours juvenile seals spent in oceanographic zones. Number in parenthesis is the percent of the total time.

		Oceanographic Zone			
Age	Sex	MIZ - SACC	SACC - APF	APF - SAF	SAF - North
<1	M	1592	2263	3910	7113
<1	F	1532	3838	5638	3656
1	M	531	437	4190	912
1	F	0	402	2140	74
Total		3655 (9.5)	6940 (18.1)	15878 (41.5)	11755 (30.7)

At any one time, the population of seals aged one year or less at Macquarie Island is approximately 14 000 (Australian Antarctic Division, unpublished data). Assuming that the foraging behavior of the seals in this study was typical of the entire population of one-year-old or less elephant seals from Macquarie Island, then in each year, 5 740 seal foraging days would be spent in un-managed high seas areas, 1 316 days in CCAMLR statistical area 58.4.1, 1 974 days in CCAMLR statistical area 88.1, 560 days in CCAMLR statistical area 88.2, 2 086 days in the MIEEZ and 2 478 days in the NZEEZs (Figure 4.8).

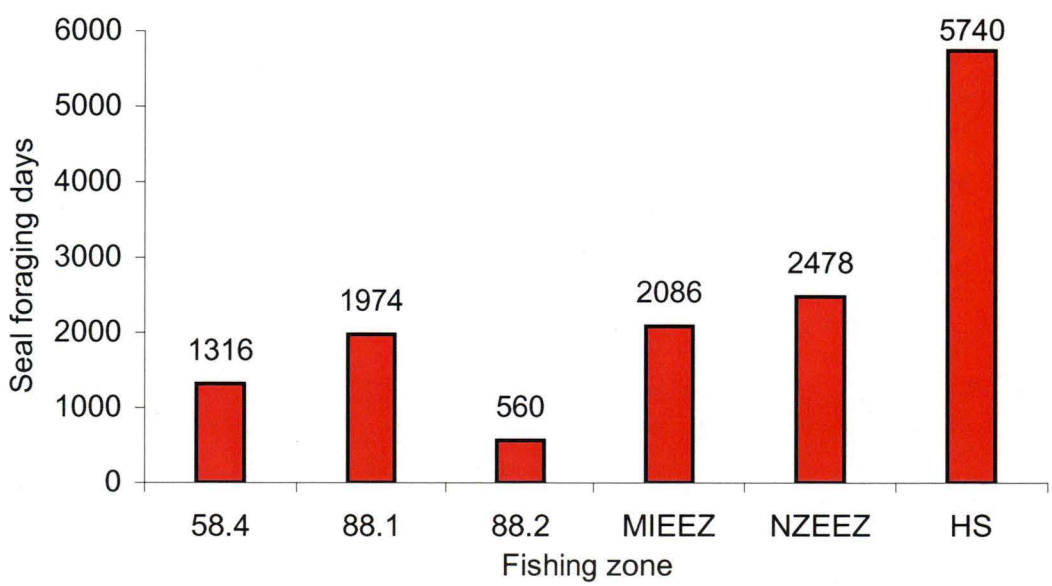

Figure 4.8: Number of foraging days (top of bar) the model population of one-year-old or younger seals from Macquarie Island spent in each of the fishery areas.

4.3.8: Diet

Prey items were identified in stomach samples lavaged from 4 of the tracked underyearling seals (Table 4.5). All prey were well digested, no stomachs contained fleshy remains. Fish, represented by eyes and scales, were present in 3 of the 4 samples collected. Squid beaks were present in the four stomachs. Two seals (♀A20 and ♂A51) which had travelled to the Campbell Plateau contained beaks of *Moroteuthis knipovitchi*, *Chiroteuthis* (unidentified species) and *Lycoteuthis lorigera*, all which are species associated with island groups or continental slopes (Table 4.5). There were no Antarctic species present in the stomach contents of the northern migrating seals. The westward migrating seal, ♂A76, contained only *Galiteuthis glacialis* beaks in its stomach. Male F995, travelling west via the ice edge, contained a similar suite of squid species to that of the two northern foraging seals, with the exception of *L. lorigera.*

Table 4.5: Prey remains and species lavaged from juvenile seals fitted with geolocation time-depth recorders at Macquarie Island.

Seal No./Sex	Foraging ground	Fish remains	Squid species (No. of beaks)	Known geographic distribution of squid species (source)
A20/F	North to STF/STR	Eyes and scales	*Moroteuthis ingens* (2)	SubAntarctic waters north of APF (a)
			Moroteuthis knipovitchi (4)	Circumpolar, oceanic, associated with island groups, to 460m (a, b)
			Lycoteuthis lorigera (2)	Circumglobal 30°N-50°S, continental slope 300-400m (C.C. Lu pers. comm., c)
			Martialia hyadesi (2)	Circumpolar Southern Ocean, S of 40°S, common APF and SubAntarctic waters. 0-1000m depth (a)
			Chiroteuthis unid. sp.* (2)	Unknown, but the beaks are common in SES stomachs from Heard and Macquarie Islands suggesting the species is associated with island groups.
			Histioteuthis eltaninae (10)	SubAntarctic, proximate to island groups 300-2000m (a)
A51/M	North to SAF/STR	None	*M. knipovitchi* (2)	As above
			Chiroteuthis unid. sp.* (2)	As above
A76/M	West to APF	Eyes	*Galiteuthis glacialis* (1)	Vicinity of APF and Antarctic waters, mid-water oceanic 100-2000m depth (a,b)
F995/M	West to IE/APF	Eyes	*M. ingens* (1)	As above
			M. knipovitchi (1)	As above
			H. eltaninae (1)	As above
			Chiroteuthis unid. sp.* (3)	As above
			M. hyadesi (1)	As above

a. Fischer and Hureau 1985. b. Rodhouse *et al.* 1992. c. Clarke 1986. * van den Hoff 2001b.

4.4 DISCUSSION

4.4.1: Survivorship and Data Integrity

Fitting GLTDRs to pinnipeds is an invasive procedure (Gott 1999) that might ultimately lower the survivorship of the study seals. The survivorship of seals fitted with a GLTDR was between 77.8 and 86.6%, depending on age (Table 4.3). First-year survival of seals branded at Macquarie Island was estimated to be in the order of 65.5% (McMahon *et al.* 1999), but a revised figure may put that figure as high as 74.3% (Table 4.3). The higher survivorship seen in this study may be due to the small sample size for this study (43 vs 14 000) or increased probability of resighting the seals because they were fitted with VHF tracking units that allowed them to be found in remote areas and in adverse conditions. Nevertheless survival of instrumented seals was high and not less than non-instrumented seals. This finding suggests the methodology used in this study did not affect the individual seals, nor population as a whole, and the data collected have a high degree of integrity.

4.4.2: Displaying Seal Positions from Geolocation Estimates

Le Boeuf (1994) suggested geolocation by light-levels – corrected with sea surface temperature – is not accurate enough to specifically place a seal at a location, and correlate that location with bathymetry, however, the method is sufficient for showing general migration direction and distance. The locations gathered by the study seals during equinox periods, when latitude cannot be determined, were corrected with reference to SST and filtered (after McConnell *et al.* 1992a) to give the best possible location for each seal on each day. As suggested by Hill (1994), each location is presented herein as a shape, in this case a 3° x 3° grid square within which locations can be assigned a 68% confidence limit (van den Hoff *et al.* in review, Chapter 3). At this scale the locations could be used to position seals relative to 1. large scale bathymetric features such as sub-marine plateaus and wide continental shelves and 2. coarse and meso-scale (100 to 100 s of km) ocean frontal systems such as the SACC, APF and the SAF; or 3. also used to relate foraging time within large scale administered fishing areas such as CCAMLR areas and New Zealand's 200 nautical mile (370 km) radial limits.

Eighteen of the 22 (82%) juvenile seals tracked by geolocation in this study were located in open oceanic waters, thousands of meters deep. For these seals, bathymetry is likely to play only an indirect role because benthic dives at these

depths are far beyond the capabilities of juvenile and adult elephant seals (Slip 1997b, Irvine *et al.* 2000). The remaining 4 seals were located over, a relatively shallower (0 – 2000 m deep) bathymetric feature, the Campbell Plateau which has an extent near 10 degrees of latitude and longitude.

4.4.3: General Migration Direction, Distance and Foraging Grounds

Juvenile seals ranged widely over the Southern Ocean, between latitudes 135°E to 150°W and longitudes 43°S and 66°S. The dispersion direction was not random ($P < 0.05$), seals preferring south to north and east to west. The average bearing was south easterly (143.5°) toward frontal zones north of the Ross Sea. Previously, foraging grounds for post-breeding and post-moult female elephant seals from Macquarie Island have been located at similar areas (Slip *et al.* 1994). The overlap and competition for food resources between pregnant females and juvenile seals is likely to be minimal because the haulout cycles differ between age classes (Hindell and Burton, 1988), however some horizontal spatial overlap may occur (Slip *et al.* 1994). Adult female seals return to breed and moult at Macquarie Island in September and January, respectively while juveniles are on the island moulting during late November to January, and have a mid-year haulout between April and August (Hindell and Burton 1988). Thus while the juvenile seals are foraging, the females are pupping and while the pregnant females remain at-sea foraging for the year, the juvenile seals have a period of mid-year haulout when a portion of the juvenile population is either at sea or on land. While at sea the adults and juveniles may be further separated because their diving capabilities differ, adults dive (and presumably forage) deeper and for longer than juvenile seals (Irvine *et al.* 2000). Older male seals forage further to the south in the Ross Sea and over the Antarctic continental shelf (Slip *et al.* 1994, John van den Hoff unpublished data) while the juveniles in this study did not.

There does not appear to be any age or sexual segregation in foraging at an early stage (< 2 years of age) in the southern elephant seal's life. Northern elephant seals do not segregate their feeding grounds until puberty (Stewart 1997). This study tracked 7 underyearling and 4 yearling male seals that foraged north of 65°S and another study tracked five male seals aged five years of age into the Ross Sea to 75°S and near the Antarctic continental shelf south of 65°S (John van den Hoff

unpublished data). Segregation in foraging appears to happen between ages 3-5 (puberty) for male southern elephant seals from Macquarie Island.

The distances covered by the seals in this study were, in most cases, greater than those reported for underyearling southern elephant seals tracked at Heard Island (over 900 km from their haulout sites, Slip 1997b), but similar to weaners (2-5 months of age) from King George Island (Bornemann *et al.* 2000) and Macquarie Island (McConnell *et al.* in review). Juveniles also ranged similar distances to adult elephant seals from Macquarie Island (1 500 – 2 880 km, calculated from maps in Hindell *et al* 1991a), Heard Island (up to 2 500 km, Slip 1997a) and South Georgia (3 000 km, McConnell and Fedak 1996). One yearling female A35 travelled to a location approximately 3 319 km from Macquarie Island (Table 4.1). Clearly, juvenile elephant seals are capable of long-distance migrations equalling or exceeding those of adults and do not remain close to Macquarie Island (van den Hoff 2001a) as suggested by Carrick and Ingham (1962). The migrations reported here are of a lesser extent than the current maximum of 10 000 km reported for a juvenile elephant seal migration from Macquarie Island (Hindell and McMahon 2000), however this record is likely to be unique and not representative of the population as a whole.

The Campbell Plateau, south and east of New Zealand, was visited by seals in this study while the ocean and islands to the near south of Tasmania, although approximately the same distance away, were not. However, juvenile seals from Macquarie Island have been recorded to haulout on coastal regions of Tasmania but their condition is often poor and some perish (van den Hoff 2001a). Occasionally adult females have pupped there, for example in October 2000 two pups were born on Maatsuyker Island to the near south of Tasmania and one pup was born on mainland Tasmania at Dover Beach. Because GLTDRs log location parameters and the return of the instruments is essential for analysis, some of those seals that failed to return during this study may have migrated to the south of Tasmania and perished there or while at sea.

Hunt (1991) suggested a concentration in the distribution and abundance of breeding and foraging seabirds might reflect the availability of prey and thus foraging areas. The same may be true for the seals tracked in this study, and there

were increases in the time seals spent in certain areas, particularly near oceanic and bathymetric locations. The geolocations can be combined with the dawn SST records to further imply foraging areas for juvenile elephant seals. If this is so then the seals forage in three ocean areas. One area was the APF and the open ocean to its north and south, another area was north of Macquarie Island over the Campbell Plateau and the associated sub-Antarctic front (SAF). The third was adjacent to the southern boundary of the Antarctic Circumpolar Current (SACC) and the marginal ice-edge zone (MIZ)

4.4.4: Antarctic Polar Front and Open Ocean

The APF and the open ocean to its north and south were the most important oceanographic features to correspond with concentrations of elephant seal locations. The APF is reported to be an area of elevated productivity where high abundances of both surface zooplankton and seabirds have been observed (Pakhomov and McQuaid 1996) and where some evidence of upwelling has been reported (Deacon 1982). The data presented here further highlight the importance of the APF for foraging to southern elephant seals from Macquarie Island (Hindell *et al.* 1991a, b; Slip *et al.* 1994) and comply with records from South Georgia (McConnell and Fedak 1996) and Marion Island (Jonker and Bester 1998). However, Jonker and Bester (1998) also found seals utilising the interfrontal zones. Four juvenile seals tracked from King George Island did not migrate to the APF. Those seals utilised bathymetric features and shifted with the advance of the ice-edge (Bornemann *et al.* 2000).

4.4.5: Campbell Plateau Region

The Campbell Plateau (CP) is located 600 km from the east to north-east of Macquarie Island and just to the north of the SubAntarctic Front (SAF). There are several island groups dotted over its area and the landmass of New Zealand is close by. Haulout sites of juvenile seals, in particular males, from Macquarie Island and foraging by adult female seals in the region has been previously documented (Slip *et al.* 1994, Field *et al.* 2001, van den Hoff 2001a,). Three young male seals were tracked over the plateau, only one female did so (Figures 4.4 and 4.5).

Cephalopod prey available to elephant seals foraging on the Campbell Plateau include: *Moroteuthis ingens*, *M. robsonii*, *Todarodes filippovae*, *Histeoteuthis* spp.,

Ommastrephes bartami and *Nototodarus sloanii* (Anderson *et al.* 1998). All these squid species except, *O. bartami* and *N. sloanii,* have been identified as prey of juvenile and adult seals (Green and Burton 1993, van den Hoff unpublished data) from Macquarie Island. The distribution of *M. ingens* is widespread over the plateau at depths greater than 200 m (Jackson *et al.* 2000). Such depths are within the dive capabilities of juvenile elephant seals (Slip 1997b, Irvine *et al.* 2000). Two juvenile seals from this study (♀A20 and ♂A51) had remains of *Moroteuthis* spp. in their stomachs when they returned to Macquarie Island. Female underyearling, A20 also had remains of *Martialia hyadesi* (closely related to *T. filippovae*), and *Histeoteuthis* sp. in her stomach.

4.4.6: Southern Boundary of the Antarctic Circumpolar Current and the Marginal Ice Edge Zone

Marginal ice edge zones (MIZs) are regions where productivity is elevated and marine predators concentrate (Hunt 1991, Stirling 1997). Juvenile elephant seals migrated toward the MIZ but did not penetrate deeply into the zone (Figures 4.4, 4.5 and 4.6). Far southern latitudes within the Ross Sea and near the Balleny Islands area are known foraging areas for adult male southern elephant seals from Macquarie Island (Hindell *et al.* 1991 a, b, Slip *et al.* 1994). Potential therefore exists for some spatial overlap between the adult and juvenile seals at the ice edge but juveniles did not penetrate the pack ice as deeply.

The presence of heavy ice cover may exclude elephant seals from the ocean waters beneath as it does near haulout sites (Burton 1985) but the ice retreat releases nutrients that encourage primary and secondary production essential to the higher predators. Remains of Antarctic squid species such as *Alluroteuthis Antarcticus* and *Psychroteuthis glacialis* have been found in the stomachs of juvenile southern elephant seals from Macquarie Island (Green and Burton 1993, John van den Hoff unpublished data). These two cephalopod species have a distribution reported to be restricted to continental shelf breaks of less than 200 to about 900 m depth (Groger *et al.* 2000). This suggests that juvenile seals are capable of migrating to and foraging in cold Antarctic waters, possibly as far as the continental shelf at least during the summer sea-ice minimum, however the squid's distribution may be more extensive than is thought. The SSTs recorded by the most southern tracked seals

during August were cold (-1.4°C) but the scale on which the locations are plotted suggests the seals were still foraging north of the continental shelf.

Tynan (1998) showed the southern boundary of the ACC is correlated with the distribution of the sperm whale (*Physter macrocephalus*), an important squid predator. Tynan (1998) suggested that the shoaling of upper circumpolar deep water (UCDW) might affect the vertical movement and availability of squid and the southern boundary is a critical trophic structure in the function of the Southern Ocean. Although elephant seals are squid predators, the limited number of hours juvenile seals spent within and south of the SACC suggests such an area is not critical to young elephant seals as some other areas.

The foraging strategies used by juvenile elephant seals tracked by geolocation from Macquarie Island are similar to geolocation and satellite tracked adults (Hindell *et al.* 1991a, Bester and Pansegrouw 1992, McConnell *et al.* 1992a, McConnell and Fedak 1996, Slip 1997a, Jonker and Bester 1998, Campagna *et al.* 1999, Bornemann *et al.* 2000). Juvenile seals ranged widely from the island and considerable time was spent near oceanic frontal systems and bathymetric features such as the extensive Campbell Plateau. None of the juveniles that returned in this study period had travelled north-west to Tasmanian waters or deep into the Ross Sea, where post-moult adult females and males have been reported to forage (Slip *et al.* 1994). The principal differences in foraging between young and older seals from Macquarie Island are that the juveniles appear to forage further west along the APF, the southern boundary of the ACC and the MIZ. They also forage further to the north-east on the Campbell Plateau.

4.4.7: Locating Foraging Grounds and Mass Gain

The migration routes described here suggest a tendency for juvenile seals to direct their travel to the south-east until they reach waters where the sea temperature is between 1 and 4° C (Figure 4.2). The APF is a discontinuity in ocean water temperature that extends from the distant west to the near south of Macquarie Island, then diverts south-east at a similar location to the ACC and Macquarie Ridge. Some seals appear to follow the 4 - 6° C isotherm, water temperatures similar to those around Macquarie Island, to forage in the south-east or the south-west. In contrast,

seals that use the nearby Campbell Plateau may locate that area by following a bathymetric feature, the Macquarie Ridge northward from Macquarie Island.

It remains unknown how southern elephant seals first find foraging areas. When departing on their maiden migration, weaned elephant seals are without individual foraging experience, however the locations from this study are from subsequent trips and are likely to reflect the seals' earlier successful foraging experiences. Successful foraging equates to mass gain. All the seals that returned in this study were survivors and the seals that were re-weighed were heavier than when they departed, their mass gain was 0.36 ± 0.03 kg.day^{-1} and 1.00 ± 0.18 kg.day^{-1} for the second and third foraging trips, respectively. The second trip mass gain rate in this study is similar to that reported by Bell *et al.* (1997) for first foraging trip mass gain. The number of samples in this study was low so no sex comparisons could be made. The differences in mass between the two sexes for southern elephant seals is not obvious early in the life of the seals (McMahon *et al.*1997) yet males are 10 times larger at breeding age. With the experience gained from the first two foraging trips the young seals are able to gain 1.00 kg.day^{-1} during their third foraging effort.

4.4.8: Diet

The stomach samples from four juvenile seals fitted with GLTDRs consisted mostly of cephalopod mandibles (beaks), and some fish remains. The fish species were not identifiable, but Myctophids contribute an unknown component to the elephant seal diet from Macquarie Island (Burton and van den Hoff in press). The identifiable cephalopod taxa were mostly species associated with island groups, the APF or subAntarctic waters of less than 2 000m depth (Clarke 1986, Rodhouse *et al* 1992, Fischer and Hureau 1985). The known distribution of the cephalopod species found supports the geolocation positions of the seals foraging localities.

The mean retention time for digesta of southern elephant seals held in captivity has been reported at around 13 hours (Krockenberger and Bryden 1994), although in other pinnipeds, hard prey parts such as cephalopod beaks may be retained in the stomach for at least 9 days (Harvey and Antonelis 1994). Adult elephant seals travel on average 110 km/day (Slip *et al.* 2001) so the stomach contents could have been taken within 60 – 1 000 km of Macquarie Island. There are difficulties in determining the relative importance of squid and fish in the diet (Green and Burton

1993, Slip 1995), and the relative importance of fish is probably underestimated because the otoliths are stomach acid soluble while cephalopod beaks are somewhat more resistant.

Of the 7 squid species identified in this study all but one was found in a larger sample of southern elephant seals from Macquarie Island (Green and Burton 1993). *Lycoteuthis lorigera* was not previously reported from southern elephant seals and is known to occur over continental slopes between 300 – 400 m deep (C.C. Lu personal communication). Two such areas within the estimated gut retention time for food in these seals are the Campbell Plateau and the South Tasman Rise south of Tasmania. *Lycoteuthis lorigera* has been caught on the Tasman Rise (C.S.I.R.O. Division of Fisheries, Hobart unpublished data). The seal (♀A20) from which this species was recovered was tracked to the Campbell Plateau. Information on elephant seal diet is poor and other techniques (such as fatty acid signatures from blubber biopsies) will be necessary to establish prey identities for seals foraging in remote foraging areas far from their haulout sites.

4.4.9: Fishing Zones, Foraging Time within These Zones and Target Species

South of Tasmania there are five zones within which regulated commercial fisheries operate. These are the Australian Fishing Zone (AFZ) surrounding Tasmania where trawl and line fisheries operate, (AFMA 1996); the Macquarie Island Economic Exclusion Zone (MIEEZ) where a Patagonian Toothfish (*Dissostichus eleginoides*) fishery operates; Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) statistical area 54.4.1 where trawling for Krill (*Euphausia superba*) takes place and CCAMLR statistical area 88.1 and CCAMLR sector 88.2 where a long-line Patagonian Toothfish fishery operates and the New Zealand Island Economic Exclusion Zone (NZEEZ) where longline, squid, Patagonian Toothfish and Orange Ruffy (*Hoplostethus atlanticus*) fisheries operate over the Campbell Plateau (Bergin and Haward 1995).

Juvenile seals in this study were tracked to these areas of the Southern Ocean where commercial fisheries operate within both managed and unmanaged areas. Of these areas, the unregulated and un-managed high seas areas are of concern with regard to identifying potential overlap and interactions between the seals and the

fisheries because juvenile seals spend most of their foraging time in these areas. Little information is available and there are no fisheries observers aboard the high seas vessels in these waters to record these types of interactions. The next most important areas were the MIEEZ and the NZEEZ followed by the CCAMLR statistical areas. However, when combined the southern CCAMLR zones were second only to the high seas in importance to juvenile elephant seals from Macquarie Island.

Interactions between marine mammals and commercial fishing activities are well documented (e.g., Wickens and Sims 1994 and references therein, Alexander *et al.* 1997, Mattlin 1994). They appear to be inevitable, especially with increases in fishing effort, new locations and the development of modern fishing techniques (Mattlin 1994), and may occur either directly between fishing gear and the animals or indirectly via prey depletion. Currently, none of the commercial species (orange roughy, gemfish, dory, trevalla, ling, arrow squid or mackerels) caught by the commercial fisheries outlined above have been identified as part of the diet of elephant seals from Macquarie Island, but the seal's diet has not been examined where these fisheries operate. In addition there have been no instances reported of elephant seals interacting with fishing gear within those fisheries.

The Patagonian toothfish is the one fin-fish fishery that has had interactions with southern elephant seals. A hook has been removed from the nose of a male seal at Macquarie Island (McMahon *et al.* 2001), one dead juvenile seal was removed from a trawl net (Australian Fisheries Management Authority records) and otoliths from toothfish have been recovered from a small number of elephant seal guts (Slip 1995).

Euphausids are the most fished for species in the CCAMLR areas (CCAMLR records). Remains of *Euphausia* spp. have been retrieved from southern elephant seals but the recoveries are rare at Heard Island (Slip 1995), but more common at the Windmill Islands (66°30'S, 110°30'E) on the Antarctic continent (John van den Hoff unpublished data). This is possibly due to the rapid digestibility of krill and the extensive distances breeding islands are located from Antarctica where the krill are located. To date there are no reports of southern elephant seals being entangled or directly interacting with the krill trawl fishery.

Although rare now such fishery interactions may escalate in the future but the interactions may be subtle. For example, krill is an important prey for most squid (Lu and Williams 1994) which in turn is a significant contributor, in terms of biomass, to the diet of many marine predators (Rodhouse 1990). Commercial fishing operations within the foraging areas of juvenile and adult elephant seals target many fish and some squid species but none are currently recognised as part of the diet of elephant seals from Macquarie Island. Some squid species have commercial potential and one species, *Martialia hyadesi* has been caught in commercial quantities (Roper *et al.* 1984, Rodhouse 1990). If a fishery is established or expands for squid species in the Southern Ocean there may be some ramifications for the major squid predators such as southern elephant seals and Sperm whales.

4.4.10: Conclusions

From this and previous studies, southern elephant seals appear to be dependent to some degree upon the Antarctic marine ecosystem for foraging. Their foraging grounds are located in CCAMLR administered waters and government regulated fishing zones near Macquarie Island. A proportion of the juvenile population forages south of 60°S and males older than three years of age feed on the continental shelf of Antarctica itself.

I have documented here the locations of foraging areas used by the juvenile portion of a decreasing population of southern elephant seals from Macquarie Island. To plot the locations and determine the important foraging areas for the seals I have used, for the first time, a spatial scale based on a 3° x 3° square grid within which 68% of the geolocations are likely to occur (van den Hoff *et al.* in review). The main foraging areas are situated south and east of the island relative to oceanographic and bathymetric features but within commercial fishing zones. Juvenile seals share some foraging areas with adult females but do not appear to forage within the pack ice as far south as adult males do. The lesser diving ability for juvenile seals (Irvine *et al.* 2000) may further reduce the overlap between certain age classes and breeding status. Survivorship for naïve weaned elephant seals may depend on them finding prey in one of the three foraging areas described herein.

Attention is drawn to the increasing possibility of seal-fisheries interactions occurring through prey depletion (Trites *et al.* 1997, DeMaster *et al.* 2001). For elephant seals, squid are the most likely taxa where future overlap is likely to occur. For example *Martialia hyadesi* has a commercial potential and is important to the seals, both adult and juvenile. One major problem with assessing fishery/seal competition is that it is extremely difficult to sample the diet of these seals while they are at sea in their "feeding areas" where the diet may be different to that observed at breeding locations. There is a need to further an understanding of their prey when the seals are at distant foraging locations such as the APFZ, south of Tasmania, south of New Zealand and in CCAMLR areas 58.4.1, 88.1 and 88.2. Such a study can be achieved by sampling seals from Macquarie Island that haulout on coasts within close proximity to these areas. Long-term telemetry studies may also reveal if individual seals revisit their known previous foraging grounds (e.g., Stewart and DeLong 1994) and how foraging strategies of the southern elephant seal change from year to year in response to fluctuations in prey abundance and distribution resulting from changes in the ocean environment.

Currently, the southern elephant seal seems to be far removed from the commercial fishing industry and the ocean features they depend upon for their foraging are of sufficient productivity such that the surviving seals tracked in this study all gained mass. Continued tracking of elephant seals and study of the seal diet will further an understanding of the degree to which human activities influence their survival and if the subtle changes in the ocean climate affects the diet, migration and survival of the seals at Macquarie Island.

CHAPTER 5

CONCLUSIONS

5.1: Study Validation

While the population of southern elephant seals at Macquarie Island continues to decrease, a long-term study of the seals has as yet to find any definable reason for the decline. Survival of juvenile seals is thought to be one contributing factor (Hindell *et al.* 1994). The survivorship of juvenile seals instrumented with a GLTDR was better than non-instrumented seals (76% vs 65.5%) but this is possibly due to the greater resightability of the seals because they had a VHF transmitter and GLTDR attached to their backs. Regardless of this the survivorship estimates suggest the instruments are not affecting the seals' ability to catch food nor is the use of these methodologies discouraging them from returning to the island, because most instrumented seals returned and those that were weighed upon their return were in better body condition than when they departed. I conclude that the attachment of geolocation devices and VHF transmitters had a negligible effect upon the individual seal. Thus, this study is a reflection of the foraging and migration behavior of juvenile seals from Macquarie Island.

5.2: Haulout Locations and Foraging Migrations

From a marking and geolocation telemetry study of juvenile southern elephant seals from Macquarie Island, I have established some important areas that these seals utilise for haulout and foraging.

Resighting tagged and branded elephant seals, marked on Macquarie Island, at locations other than their natal island has allowed some determination of the basic age-related dispersal patterns and migration behavior. Most of the haulout sites are located within 1 000 km of Macquarie Island mainly on the New Zealand sub-Antarctic islands, and in particular Campbell Island. Emigration from the Macquarie Island population appears to be very low (0.53%), and the age-class most likely to disperse are young males.

Juvenile elephant seal foraging areas are situated both within regulated and unregulated commercial fishing zones mainly to the south-east of the island. The

seals' migrations take them to foraging grounds distant from Macquarie Island into waters adjacent with coarse to meso-scale ocean fronts and bathymetric features such as the Campbell Plateau. Juvenile seals of both sexes migrate south toward the Antarctic continent where they forage in waters between 1.0° and 4.0 ° C. Their foraging grounds are to the north of adult males but similar to adult females. CCAMLR managed fishery areas are important foraging areas for elephant seals from Macquarie Island. The survival of southern elephant seal pups from Macquarie Island may be linked to them finding prey in one of the three general areas identified in this study, and the continued absence of commercial squid fisheries in the Southern Ocean to the south of Macquarie Island.

It is encouraging for the conservation of this species that the seals are foraging in regulated and managed fishing areas and the degree of species overlap between the fisheries and the seals is, at the moment, small. However, the seals' future is uncertain because some species of fin-fish and squid that are prey for southern elephant seals also have commercial possibilities. Commercial fisheries have a history of collapse through overfishing of target species (DeMaster *et al.* 2001) and as the demand for food rises the southern ocean's fin-fish and cephalopod stocks may well become attractive and commercially viable.

5.3: Geolocation as a Method for Displaying the At-Sea Position of Southern Elephant Seals

Tracking the movements of free ranging juvenile southern elephant seals by geolocation is coarse but can still yield valuable data for management and conservation purposes. The resolution at which the seal's movements can be plotted and analysed with regard to ecological and economic regions is within a square grid 3° x 3° (ie. ± 1.5°) of latitude and longitude. I have calculated that 68% of geolocation estimates will occur in this sized grid. For greater confidence (ie. 95%) the scale is coarser, in the region of ± 2.5°.

5.4: Potential Prey Overlap between Elephant Seals and Commercial Fisheries: a Precautionary Comment. (Note: Portions of this section have been submitted in a recent paper by Burton and van den Hoff in press, Australian Mammalogy).

Potential interactions between commercial fisheries and southern elephant seals include (i) Competition for prey resources (overlap between the seals' prey and species targeted by the fishery) and (ii) direct interactions with fishing gear. Southern elephant seal diet investigations are few and some describe only the cephalopod component in their diet because the beaks are robust and readily identifiable (e.g., Rodhouse *et al.* 1992, Daneri *et al.* 2000). The diet appears to be dominated by cephalopods with fish and crustaceans contributing an unknown proportion. Identifiable fish remains, such as otoliths, and crustaceans are relatively digestible and thus are likely to be under-represented in stomach samples. Furthermore, no studies have been published that describe the diet of elephant seals at New Zealand's sub-Antarctic islands nor from the fourth largest colony at Peninsula Valdés, Argentina where commercial fisheries operate.

None of the squid species found in the stomachs are part of a current large southern fishery operation, but *Martialia hyadesi* and *Todarodes filippovae* have been caught commercially or as by-catch (Roper *et al.* 1984, Rodhouse 1993) and may continue to be fished. Of the remaining cephalopod species, nine (45%) have been identified as suitable for commercial fishing (Table 5.1) and there are fisheries for members of the same families elsewhere in the world (Rodhouse 1990).

After 6 years of collections at Macquarie Island, the first toothfish (*Dissostichus* sp) otoliths have been recovered from about 400 seal stomachs (Iain C. Field, personal communication).. Otoliths of *D. eleginoides* have also been found in three of 79 southern elephant seals sampled from Heard Island (Slip 1995). The rarity of toothfish (it is currently unknown if the species is *D. mawsoni* or *D. eleginoides*) indicates it is either not important in the diet or the remains are well-digested prior to our sampling, having been consumed at locations far from the sampling sites. The commercial toothfish fishery has only a small overlap with the elephant seals (Goldsworthy *et al.* 2001).

There are four species of fish eaten by southern elephant seals that are commercially exploited (Table 5.2). Their commercial value is as fish-meal to be used for the feeding of animals. These species are likely to be more exploited in the future, as the world demand for food from the oceans continues to rise others, eg *Channichthys rhinoceratus*, which have been assessed as having some commercial value, may join them. The fish species taken by both elephant seals and fisheries are benthic (e.g., *Notothenia squamifrons*) or benthopelagic (e.g., *Dissostichus eleginoides* and *Champsocephalus gunnari*). These species occur over continental and island shelves, slopes and plateaus near sub-Antarctic islands (Fischer and Hureau 1985) where the seals have been sampled by stomach lavaging. Therefore, it would be expected that, if those fish species were eaten to any considerable extent then their otoliths would be found more commonly than they have been (frequency of occurrence <5%). Alternatively, the seals may be feeding on these species during the outward part of the foraging migration directly after a lengthy fasting period but not on the return leg when the seals have fattened and thus the digestion of their remains is complete. It is also possible that myctophid fish are seen in their diet, to some extent, as a result of secondary ingestion by squid. Myctophid fishes are an important component in the diet of the squid *Moroteuthis ingens* around Macquarie and Heard islands (Phillips *et al.* 2001) and New Zealand (Jackson *et al.* 1998). *Moroteuthis ingens* is itself important as prey for southern elephant seals.

There is little real time diet data for southern elephant seals when at their major foraging grounds in the pelagic zone and over the Antarctic continental shelf (McConnell *et al.* 1992, Slip *et al.* 1994, Jonker and Bester 1998, Campagna *et al.* 1999, Chapter 4) and within the economic exclusion zones described herein. If these existed, comparisons of the diet distant and local to the breeding islands could be made and the relative degree of dependence that elephant seals have upon any region or prey species, particularly those of commercial interest, could be determined. For example, studying the diet of elephant seals from Macquarie Island at Campbell Island and Antipodes Island may reveal the importance of commercially fished species such as Orange Roughy and arrow squid (*Nototodarus sloani*) to the diet. Seals breeding on Marion Island, Peninsula Valdés, and Falkland Islands also have yet to be sampled to assess the importance of commercial species such as Patagonian Toothfish and the squid *Illex argentinus* in their diets.

In 1998 the world harvest of *I. argentinus* was approximately 650 000 tonnes from the Patagonian Shelf (FAO 2000) in the south west Atlantic sector of the Southern Ocean and no diet studies of southern elephant seals have been carried out there. The population of southern elephant seals at Peninsula Valdés is increasing (Lewis *et al.* 1998) so the vigorous *Illex* fishery appears to have little effect on the seal population so far. Male southern elephant seals from Peninsula Valdés dive to the sea bottom over the Patagonian shelf and to mid-water depths (Campagna *et al.* 1999) whilst depth distribution of *I. argentinus* is from the surface to 800m (Roper *et al.* 1984). Spatial overlap therefore seems highly probable, but this situation is likely to be different for each elephant seal population as fish species and their proportions are different and the various age classes feed in different areas.

Trites *et al.* (1997) reported a 35% diet overlap between the marine mammals in the Pacific Ocean and the fisheries there, and this was far less than expected considering the frequent complaints about marine mammals by some fishers. At present there is commercial interest in 18% of the prey species in the diet of southern elephant seals; while this might not appear to be severe but they are the species that contribute a large proportion of the prey biomass the seals consumed. One species, *Martialia hyadesi*, can account for as much as 94% of the biomass. Clearly there is cause for some concern if a directed fishery escalates or the by-catch of *M. hyadesi* and *Todarodes filippovae* in the *Illex*, *Nototodarus* and toothfish fisheries increases.

Crustacean species common to southern elephant seal diet and fisheries are shown in Table 5.2. One of the three Euphausiidae, *Euphausia superba,* is of commercial value and is currently harvested. The frequency of occurrence (FOO) of euphausids in the diet of southern elephant seals is low, at Heard Island it was 12% and the biomass consumed appears insignificant (Slip 1995). But the fact that most diet studies have been carried out at the seals' breeding sites may lead to an under-estimation of the importance of rapidly digestible species such as krill. The relatively undigested krill (*E. crystallorophias*) remains found in stomach samples collected at the Windmill Islands (John van den Hoff unpublished data) suggests direct ingestion rather than secondary ingestion. Krill fishing in Antarctic waters is regulated by the CCAMLR. *Euphausia superba* is the commercial krill species and has been harvested from seas surrounding the Antarctic continent; but the areas of

concentrated fishing are now the South Atlantic, along the Antarctic Peninsula and South Georgia (Nicol and Endo 1997). Regardless of whether krill are directly ingested or not, they are a pivotal component to the Antarctic ecosystem (Nicol and Endo 1997) and the prey of southern elephant seals are themselves largely reliant upon krill. Again the relative importance of krill to southern elephant seals, directly or indirectly, is poorly understood and thus the expansion of a krill fishery has uncertain consequences.

Entanglement and direct mortality interactions between marine mammal and commercial fishing activities are well documented (e.g., Wickens and Sims 1994 and references therein, Alexander *et al.* 1997, Mattlin 1994), however interactions of this type are few with respect to southern elephant seals (Burton and van den Hoff in press). Two probable interactions concerning seals from Macquarie Island have been reported, one long-line hook has been removed from a sub-adult male elephant seals' nose (McMahon *et al.* 2000) and one dead seal recovered from a trawl net from a commercial operation near the island itself.

The Southern Ocean region adjacent the Ross Sea and the Antarctic continent is an area where important foraging areas are located for southern elephant seals from Macquarie Island. Antarctic species that forage in this region would benefit from the establishment of a reserve within which commercial fishing is excluded. For example, the 150°E and 150°W meridians, the 55°S parallel and the coastline of Antarctica could bound the area, the challenge is in establishing such an area.

Table 5.1: Cephalopod taxa identified from beaks recovered from the stomachs of Southern Elephant Seals (*Mirounga leonina*). Frequency of Occurrence (FOO) and Importance by Mass (IBM) are give as the percent range if the species was present in the published data. Y = yes, N = no, ? = unknown. From Burton and van den Hoff (in press)

CEPHALOPOD SPECIES	FOO (%)	IBM (%)	COMMERCIAL QUANTITIES CAUGHT [3,5,9,10,11,12]	SUITABLE AS A COMMERCIAL SPECIES [3,5,10,9,11,12]
Alluroteuthis antarcticus [2,4,6,7,8]	11 - 78	0.3 – 35.0	N	Y
Brachioteuthis sp. [2,4,6,7,8]	3 - 67	0.1 – 0.5	N	**Y**
Chiroteuthis ssp. [2,4,6,7,8]	8 - 33	0.02 – 0.6	N	N
Galiteuthis glacialis [1,2,4,6,7,8]	0.5 - 38	0.1 – 2.7	N	N
Gonatus antarcticus [1,2,4,6,7,8]	9.4 - 71	0.9 – 3.9	N	**Y**
Histeoteuthis eltaninae [2,4,6,7,8]	3 - 89	0.1 – 37.3	N	N
Kondakovia longimana [1,2,4,6,7,8]	5 - 71	2.6 – 71.8	N	**Y**
Liochranchia sp. [7]	17	0.01	N	N
Martialia hyadesi [2,4,6,7,8]	5 - 25	0.2 – 94.4	**Y**	**Y**
Todarodes filippovae [2,4,6,7,8]	4 – 22	0.1 – 56.6	**Y**	**Y**
Mastigoteuthis sp B [2,4,6,7,8]	3	0.01	N	N
Chiroteuthis sp. [8]	9 - 67	0.2 – 2.9	N	N
Moroteuthis ingens [2,4,6,7,8]	3 - 67	0.7 – 50.4	N	**Y**
Moroteuthis knipovitchi [1,2,4,6,7,8]	5 - 71	3.9 – 43.7	N	**Y**
Pholidoteuthis boschmani [2,4,6,7,8]	5	0.3	N	**Y**
Psychroteuthis glacialis [1,2,,4,6,7,8]	6 - 100	0.2 – 81.4	N	**Y**
Taonius pavo [2,4,6,7,8]	6 - 17	0.01 - 0.6	N	?
Pareledone polymorpha [1,6]	12.5	4.2	N	?
P. charcoti [1,6]	37.5	13.2	N	?
P. turqueti [1]	12.5	4.2	N	?

[1] Clarke, M.R. and McLeod, N.1982. [2] Daneri, G.A., Carlini, A.R. and Rodhouse, P.G.K. 2000. [3] Fischer, W. and Hureau, J.C. 1985. [4] Green, K. and Burton, H.R. 1993. [5] Rodhouse, P.G.K. 1990. [6] Rodhouse, P.G.K. *et al.* 1992. [12]Roper *et al.*, 1984, [7] Slip, D.J. 1995. [8] van den Hoff, J. and Burton, H.R. unpublished data from Macquarie Island. [9] van den Hoff, J. 2001b. [10] Wadley, V. 1990. [11] Wadley, V and Dunning, M.

Table 5.2: Fish and Crustacean taxa identified from remains recovered from the stomachs of Southern Elephant Seals (*Mirounga leonina*). Y = yes, N = no, ? = unknown. From Burton and van den Hoff (in press).

FISH SPECIES	FOO	COMMERCIAL QUANTATIES CAUGHT .[1,4]	SUITABLE AS A COMMERCIAL SPECIES.[1,4]
Bathylagidae			
Bathylagus sp. [2,3]		N	?
Myctophidae			
Electrona Antarctica [2,3]	3	N	?
E. subaspera [2,3]		N	?
E. carlsbergi [2,3]	12	**Y**	**Y**
Electrona sp. [2,3]		N	?
Gymnoscopelus braueri [2,3]		N	?
G. nicholsi [2,3]	4	N	?
Gymnoscopelus sp. [2,3]		N	?
Nototheniidae			
Notothenia squamifrons [2,3]		**Y**	**Y**
N. acuta [2,3]		N	N
Nototheniops mizops [2,3]		N	N
Dissostichus eleginoides [2,3]	4	**Y**	**Y**
Channichthyidae			
Channichthys rhinoceratus [2,3]		N	**Y**
Champsocephalus gunnari [2,3]	<5	**Y**	**Y**
CRUSTACEAN SPECIES			
Euphausia crystallorophias [2,3]	7	**N**	**?**
Euphausia superba and *vallentini* [2,3]	12	**Y**	**Y**
Pasiphaea rathbunae[1]	?	N	N
Parathemisto gaudichaudii[2]	21	N	N

[1]Fischer, W. and Hureau, J.C. 1985, [2]Green, K. and Burton, H.R. 1993, [3]Slip, D.J. 1995, [4]Richard Williams personal communications.

CHAPTER 6

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